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THE BEHAVIOR OF INCLUSIONS IN IGNEOUS MAGMAS

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INTRODUCTION

Many igneous rocks contain inclusions of foreign material and not infrequently these inclusions show evidence of having been attacked by the magma, some to a moderate extent and others to such an extent that only traces of the inclusion remain. To some petrologists these inclusions are but the remnant of a great host, most of which has been completely incorporated in the magma, and to such incorporation or assimilation of foreign matter they would assign the principal variations of igneous rocks. The variations are not usually regarded by these petrologists as the result of assimilation alone but of assimilation followed by the differentiation of the syntectic magma which is supposed to have special powers of differentiation not possessed by the original magma. Other petrologists believe that magmas cannot be expected to have the energy content necessary for the solution of a significant amount of foreign material; that the amount of solution actually observed at and near contacts is an approximate measure of the total and that the variations of igneous rocks are quite independent of these slight additions, being due to spontaneous powers of differentiation possessed by original, uncontaminated magmas.

In the present paper it is proposed to discuss the behavior of inclusions with special reference to these questions. By application of the principle of the reaction series, as developed in a former paper,[1] it is hoped to effect a certain amount of reconciliation of these extreme views.

HEAT EFFECTS OF SOLUTION

Since one of the important questions involved is that relating to the heat effects resulting from solution it is desirable to consider the information available on these effects. The ordinary equilibrium diagram, commonly regarded as a freezing-point diagram, is at the same time a solubility diagram. It gives the change of solubility of any phase with temperature. But the change of solubility with temperature depends mainly[2] on the heat effect involved in solution and the equilibrium diagram contains complete information on this heat effect. Unfortunately the information may be very difficult of extraction; in the present state of knowledge, often impossible. One solubility diagram, that of the plagioclase feldspars, has proved particularly simple in this respect. This diagram is shown in Figure 1, the curves being calculated on the basis of a latent heat of 104.2 cal. per gram for anorthite and 48.5 cal. per gram for albite. The determined points are given by the small circles and their correspondence with the calculated curves is very remarkable. Since the curves were calculated on the basis of constant latent heats (solution heats) this correspondence simply means that

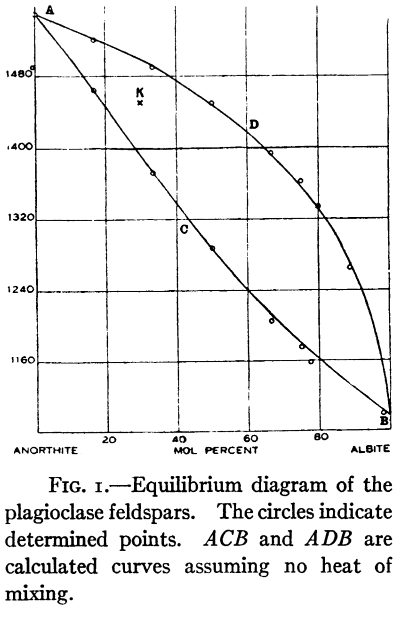

Fig. 1.—Equilibrium diagram of the plagioclase feldspars. The circles indicate determined points. *ACB* and *ADB* are calculated curves assuming no heat of mixing.

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[1] N. L. Bowen, *Jour. Geol.*, Vol. XXX (1922), pp. 177–98.

[2] The volume change is involved also but is relatively unimportant.

there are no mixing-heat effects and that the heat of solution of any plagioclase in liquid plagioclase is simply the latent heat involved in the change from solid to liquid.[1]

In Figure 2 is plotted the equilibrium diagram for anorthite and diopside. Now we know the latent heat of anorthite from the calculated results of Figure 1 and we may calculate, using this value, a curve of freezing-point depression for anorthite according to the equation for ideal concentrated solutions, viz.:

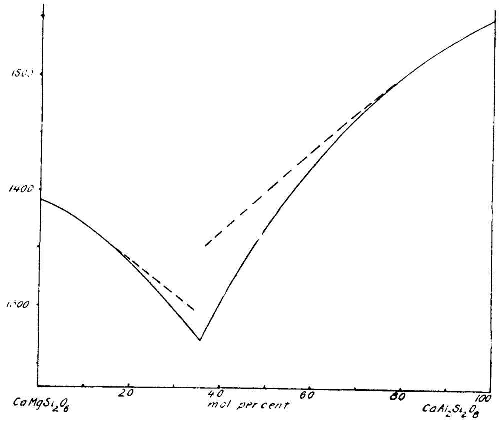

FIG. 2.—Equilibrium diagram of diopside and anorthite. Determined curves in full lines. Broken curves calculated on the assumption of no mixing heats.

$$T = \frac{T_0}{1 - \frac{2T_0}{Q} \ln x}$$

where T is the melting temperature (saturation temperature) of anorthite in a solution of mol fraction x in anorthite; Q is the latent heat of melting per mol of anorthite (=29,000 cal.) and T_0 its melting-point (=1550°). As a result of this calculation we obtain the right-hand dotted curve. It will be noted that the determined curve corresponds with the calculated dotted curve in the upper portion (as far as about 80 per cent anorthite) and then falls below. In other words, we could have calculated the latent heat of anorthite from a point on the upper portion of the determined curve. If now we do this for the diopside curve, that is, calculate the latent heat of diopside from a point on the upper portion of its solubility curve, we find a latent heat of 23,420 cal. per mol or 108 cal. per gram.[1] Calculating the further course of the curve with the use of this value we obtain the dotted curve. This calculated curve also lies above the determined curve at points distant from pure diopside. There is one factor which can cause such a deviation of the freezing-point curve from the theoretical curve of the above equation, viz., a heat of mixing of the liquids, and Van Laar has developed an equation which enables one to calculate the differential heats of mixing involved. The equation is

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[1] See N. L. Bowen, Melting phenomena of the plagioclase feldspars. *Amer. Jour. Sci.*, Vol. XXXV (1913), p. 590.

$$T=T_0\frac{1+\dfrac{a(1-x)^2}{[1+r(1-x)]^2}}{1-\dfrac{2T_0}{Q}\ln x}$$

where a and r are coefficients from the Van der Waals equation of state for binary mixtures. The numerator gives the number of times the solution heat, at the concentration x and temperature T, is greater than the melting heat Q, and the difference between this and Q is the differential heat of mixing.[2] From this equation we find the following values of the differential heats of mixing per mol (q).

TABLE I

MOLAL DIFFERENTIAL HEATS OF MIXING IN ANORTHITE-DIOPSIDE MIXTURES

For anorthite	x..........	0.8	0.5	0.4	0.35
	q (cals.).....	100	600	1100	1250
For diopside	x..........	0.7	0.65	....	....
	q (cals.).....	120	340	....	....

Now these differential heats of mixing are the heats of mixing of one mol of liquid with a very large amount of solution of the various concentrations referred to. These in themselves have no particular interest from the present point of view but from them the so-called integral heats can be calculated by a graphical method. Roozeboom[1] shows that if the curve of integral heats of mixing is plotted against mol fractions of the components then the intercept on the heat axis of the tangent to the curve gives the differential heat of mixing for the composition represented by the point. Thus in Figure 3 if the curve *ABC* represents the heats of mixing of diopside liquid and anorthite liquid in various proportions to form one mol of mixture, then the differential heat of mixing of one mol of anorthite in a large amount of liquid of the mol fraction *x* is given by the intercept on *CE* of the tangent at *x*. Also the differential heat of solution of diopside in this same mixture is given by the intercept on *AD* of the same tangent. Now in our particular case we have determined the differential heats by calculation from the freezing-point curves and we wish to know the integral heat. This is the reverse of the above problem and while not as straightforward can nevertheless be solved in the same way. We have, fortunately, for the composition of the eutectic, the differential heats of mixing for both diopside and anorthite which completely fixes the tangent at the composition of the eutectic. Figure 3, which has been referred to for purposes of illustration, is also the actual figure for diopside and anorthite determined graphically from

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[1] A direct determination by W. P. White gave 106±15 cal. *Amer. Jour. Sci.*, Vol. XXVIII (1909), p. 486.

[2] *Z. physik. Chem.*, Vol. VIII (1891), p. 188.

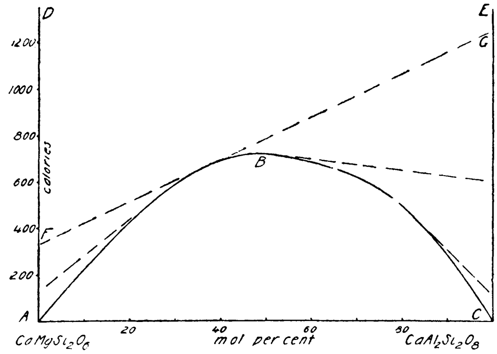

FIG. 3.—Curve of integral mixing heats of diopside and anorthite liquids (*ABC*). Showing graphical method of determining integral mixing heats from differential mixing heats.

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[1] *Die Heterogenen Gleichgewichte*, Zweiter Heft, Erster Teil (1904), pp. 287–90.

the calculated differential heats of Table I. Thus *FG* is the tangent at the composition of the eutectic joining the value of the differential heat of mixing for diopside liquid in the eutectic with the differential heat of mixing for anorthite liquid in the eutectic liquid. This fixes immediately that the integral heat of formation of one mol of the eutectic liquid from its liquid components is 650 cal. Knowing that the curve of integral heats is tangent to this line at $x=0.65$, we may readily draw a complete curve (the envelope of the family of tangents) that satisfies the known values of the differential heats. When this is done we get the curve *ABC*. This curve, then, gives us directly the amount of heat evolved when liquid anorthite and liquid diopside are mixed in any proportion. Thus when $\frac{1}{4}$ mol diopside liquid is mixed with $\frac{3}{4}$ mol anorthite liquid 500 calories are evolved. The maximum amount of heat per molecule of mixture (720 cal.) is evolved when about .047 mol of anorthite liquid is mixed with 0.53 mol of diopside. This happens to be about equal weights, so that the maximum amount of heat is evolved when about equal weights are mixed and is equal to about 3 cal. per gram of mixture. This heat is sufficient to heat the mixture about 10°.

If now we turn to the equilibrium diagram of diopside and albite and calculate a curve of freezing-point depression for diopside, using the value of the latent heat found from the anorthite diagram, we find again that the calculated curve coincides with the observed curve in its upper portion and then deviates from it (Fig. 4), but in this case in the opposite direction to that found for the other diagram. Again, this deviation can be interpreted as due to a heat of mixing of the liquid but now of the opposite sign. If we apply the Van Laar equation we can calculate the differential heats and from these determine graphically as before the integral heats of mixing. Thus we get Figure 5.

We find, then, that albite liquid and diopside liquid mix with absorption of heat, the maximum absorption (790 cal.) taking place when 0.48 mol albite is mixed with 0.52 mol diopside. This also is about equal to 3 cal. per gram of mixture.

Assuming that the theoretical basis of our calculations is to be relied upon we have proved that anorthite and diopside, both characteristic molecules of basic rocks, mix in the liquid state with evolution of heat, whereas albite, one of the most characteristic molecules of acid rocks, mixes with diopside in the liquid state with absorption of heat and with anorthite without significant heat effect.

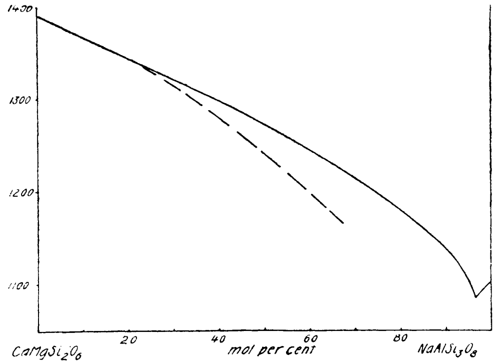

FIG. 4.—Equilibrium diagram of diopside and albite. Determined curves in full lines. Broken curve calculated on the assumption of no mixing heats.

These results are quite the opposite of what is often assumed to be the case. Many statements are to be found in the literature to the effect that acid and basic rock material will mix with evolution of heat. There is nothing in the results of studies of phase equilibrium

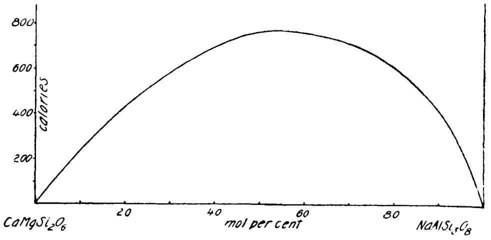

FIG. 5.—Curve of integral mixing heats of diopside and albite

to warrant such a statement; indeed, there are, as we have seen above, good reasons for doubting it.

Possibly in rare cases, where more fundamental reactions are involved, greater heats of mixing are available, but the mixing of two liquids has, in itself, little importance in petrogenesis. Our particular interest lies in the heat effect on mixing solid rock-matter with liquid magma. In that connection, however, the heat of mixing of liquids is not without significance, for the heat of solution of a solid is to be regarded as the resultant of two heats, the heat of melting of the solid and the heat of mixing of the liquids. Now the heats of mixing that we have calculated above are really very insignificant as compared with the heats of melting of the solids, and the heats of solution of the solids are, therefore, very nearly equal to the latent heats of melting. For the solution of solid anorthite in diopside a little less than the latent heat is required, for the solution of solid albite in diopside a little more than the latent heat is required. The differences are noteworthy in connection with any theory that postulates an evolution of heat when an acid rock is immersed in basic magma, but for the purposes of the present inquiry which seeks to find merely the order of magnitude of the heat effect when solid rock is added to magma, we may state that the heat of solution of solid anorthite, albite, or diopside in any liquid mixture of them is substantially equal to the latent heat of melting. Moreover it is probably true of silicates in general that the solution of the solid is attended by a large absorption of heat, though not many determinations lend themselves to interpretation in the same way as the above. Thus when one attempts similar calculations from the equilibrium of anorthite with nephelite and of anorthite with silica it is found necessary to assume molecular association in nephelite and silica, and, while this is not surprising since both occur in more than one crystal form, it nevertheless so complicates the case that interpretation becomes impossible. One thing is certain, namely, that all the solubility curves of silicates yet determined show a marked increase of solubility with temperature, which means a strong absorption of heat upon solution. No example of retrograde solubility is known. In conclusion, then, we may state that the solution of a silicate in a magma is usually accompanied by a large absorption of heat, probably of the order of magnitude of the heat of melting.

THE QUESTION OF SUPERHEAT

Having thus arrived at a general conception of the heat required for solution we may consider the question of the heat available. One aspect of this is concerned with the superheat of the magma, that is, the excess of temperature above that at which crystallization begins. Somewhere within the earth there is material (whether a rigid liquid or a crystalline solid we need not here consider) which is capable of becoming fluent liquid upon release of pressure. At great depths there may be excessively hot material capable of giving excessively hot liquid, but this is hardly concerned with matter that ever comes to the light of day as an igneous rock. There must be a transition zone representing a passage from stable crustal material incapable of becoming magma, through a zone capable of giving magma with some suspended crystalline matter, to a zone capable of giving a completely molten magma. It is from the zone giving rise to magma with some suspended crystals, rather than from the zone giving a simple liquid, that we must expect the great upwellings of magma to come, because of the advanced position of the partly crystalline material with respect to an action producing such upwelling and because it may be readily mobile when the amount of suspended crystals is small. As the magma rises in the crust several factors may combine to reduce the amount of crystals. Among these factors is the increased solubility of the crystals resulting from the lowered pressure, for the solution of silicates usually takes place with increase of volume. Besides this there may be an actual addition of heat as a result of the Joule-Thomson effect[1] and of possible exothermic reactions ensuant upon reduced pressure. It is probable that, in the usual case, the magma still retains some crystals even when it rises to shallow depths within the crust for, though the intensity of the above actions is thereby increased, it is also passing into colder and colder surroundings and must lose a corresponding amount of heat. It is possible that in some cases a magma may have lost all its crystals by the time it has risen to shallow depths and perhaps may have a temperature above the saturation temperature under the conditions there prevailing. However, even if we make the liberal assumption that it is superheated 100° (say its temperature is 1100° and the saturation temperature 1000°) and that this condition is acquired when it has reached a level 5 km. below the surface, it should be noted that the mere immersion of blocks of country rock amounting to about

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[1] L. H. Adams, *Bull. Geol. Soc. Amer.*, Vol. XXXIII (1922), p. 144.

10 per cent of the mass of magma would be sufficient to wipe out this superheat, for the original temperature of blocks even at this quite considerable depth would be only 200°.

This, too, is quite apart from the amount of heat that must be lost by the magma in heating up a large amount of wall rock other than the immersed fragments. If we consider greater depths, where the surroundings would be at a higher temperature, it must be remembered that we are thereby limiting the amount of superheat that may have been acquired as a result of those processes attendant upon the rise of the magma and proportional in amount to the extent of rise.

It is plain that there can seldom be more than a very small amount of superheat left after the heating up of immersed fragments. Occasionally, perhaps, such small amounts may be available for the direct solution of fragments but it would require only an excessively small amount of solution to use up this heat, a fact that becomes apparent when the enormous discrepancy between the specific heats of silicate liquids (0.2–0.3 cal.) and the solution heats of silicates (50–125 cal.) is realized.

We have thus deduced, from general considerations, that magmas cannot be expected to have much superheat and in particular that they cannot retain a significant amount after the immersion of foreign fragments in such quantity that an important effect upon the composition of the magma would ensue if solution did occur. This deduction need not be regarded as contradictory to the observed fact that on very rare occasions inclusions of foreign rock have been found converted into glass by magmas and that the measured temperatures of lavas at certain active volcanoes are sometimes high enough to indicate a condition probably significantly above that of beginning of crystallization. It is becoming increasingly apparent that in central volcanoes there are sources of heat, probably from exothermic gas reactions, that are capable of producing the temperatures observed, but these must be regarded as locally concentrated where the gases have their vent. Moreover, inclusions converted to glass are found almost exclusively in such extrusive rocks. Even their rare appearance in intrusive masses need not militate against the general conclusion reached, for, admitting a certain amount of superheat, the first few inclusions added would receive the full benefit of it and might be fused, but the magma would suffer a correspondingly marked loss of heat. In other words, the net result of the addition of an amount sufficient to produce a significant change of composition, say 10 per cent, would be the same even though they were added slowly and the first additions were drastically affected. Not only do magmas commonly fail to convert inclusions into liquid but they also fail to effect such changes as the transformation of quartz into tridymite and of wollastonite into pseudo-wollastonite, which fact must be regarded as indisputable evidence of the prevailing low temperatures.

There seems no reason, therefore, to doubt that direct solution of foreign material in superheated magmas cannot be a factor of importance in petrogenesis. However, the importance of superheat has been greatly exaggerated both by those who adhere to the view that magmas dissolve large quantities of foreign matter and by those who deny it. We shall find in the sequel that even saturated magmas may produce very marked effects in the way of incorporation of foreign material.

EQUILIBRIUM EFFECTS BETWEEN "INCLUSIONS" AND LIQUIDS IN INVESTIGATED SYSTEMS

In the following discussion of the effects of liquids upon inclusions, whose composition is embraced within investigated systems, attention will be confined, unless otherwise stated, to saturated liquids. This is done because we have found in the foregoing discussion that the superheated condition has little importance in nature. But lest it be thought that this is going too far in the way of eliminating superheat we have made another assumption that should amply compensate, namely, that the inclusions are already heated to the temperature of the liquid before immersion in it.

It is proposed to discuss the magnitude of the heat effects involved when reactions go on between solid inclusions and liquid in systems that have been experimentally investigated and where the equilibrium relations at various temperatures and the approximate heat effects are known. It is not expected that the numerical results so obtained will have any direct applicability to natural magmas, but it is hoped that some principles of general significance may be thereby brought to light.

As a beginning we shall refer to equilibrium in the plagioclase feldspars which is given in Figure 1. In the figure we note that liquid of composition Ab_1An_1 begins to crystallize with the separation of crystals of composition about Ab_1An_4. As the cooling proceeds, if perfect equilibrium obtains, the crystals will be made over by the liquid so that the composition of the crystals changes along the curve *ACB*. It is plain, then, that if one had a mass of liquid Ab_1An_1 at 1450°, that is just saturated, and added to this mass some crystalline material of the composition Ab_1An_4 (approx.) (already heated to 1450°) which we shall now call foreign inclusions, the liquid would, if perfect equilibrium were attainable, make over these inclusions as the temperature fell so that their composition followed the curve *ACB*. How much of this work the liquid will be able to accomplish in any individual case will depend on such factors as the size of the inclusions, their permeability to the liquid, and the rate of cooling, but the tendency is very plain. We can thus have a liquid exerting a marked influence upon inclusions even though these are precisely of the composition in equilibrium with the liquid, provided the solid is a member of a solid solution series. It should be noted, however, that this action is without effect on the course of the liquid. The composition of the liquid follows the curve *ADB* whether the inclusions are present or not. The career of the liquid may, however, be brought sooner to a close as a result of reaction with the inclusions, that is, the liquid may be entirely used up at a somewhat higher temperature.

We may now examine the case of adding to a plagioclase liquid some solid plagioclase more calcic than that with which the liquid is in equilibrium. To 50 g. liquid Ab_1An_1 at 1450° (just saturated) let us add 50 g. solid Ab_1An_9, already heated to 1450°. Equilibrium will be established, if the temperature is kept constant, only when the solid is completely changed to that with which the liquid is in equilibrium, Ab_1An_4 (approx.). Since the total composition is represented by the point *K* we can easily determine the proportions of liquid and crystals. They will be 17 per cent liquid of composition Ab_1An_1 and 83 per cent plagioclase of composition Ab_1An_4

(approx.). We have now 66 g. An and 17 g. Ab in the crystalline state. We had formerly only 45 g. anorthite and 5 g. ablite. Equilibrium will therefore be established with evolution of heat to the amount of $21\times104.2+12\times48.5$ cal. In order to keep the temperature constant, then, we should have to abstract 2770 cal. If, on the other hand, no heat were abstracted the temperature would rise somewhat and equilibrium would be established at a slightly higher temperature. For the particular case we have assumed we may readily calculate that equilibrium would be established at about 1465°, when the mass would consist of about 60 per cent crystals of composition Ab_1An_5. Even when the reaction takes place adiabatically, there is an increase in the proportion of crystals. The reaction is in no sense a solution of foreign material. Rather by a making over of the foreign material it becomes no longer foreign but identical with the crystalline matter with which the liquid is in equilibrium. Moreover, if the originally foreign matter is more calcic than the crystals with which the liquid is in equilibrium the reaction is an exothermic one. How much of this reaction would take place in any individual case cannot be predicted. It will depend upon rate of cooling and other factors that readily suggest themselves, but there is plainly a tendency toward such a reaction and the reaction is exothermic.

Let us now examine somewhat more minutely into the cause of this exothermic reaction and we shall find that it is due to a general principle and is not dependent upon the particular properties of the plagioclase series discussed. During the crystallization of a plagioclase mixture a small decrement of temperature results in the reaction:

plagioclase+liquid=a little more plagioclase of somewhat more sodic composition.

Since this is an *equilibrium* reaction taking place with falling temperature, it must be exothermic. When we add the plagioclase Ab_1An_9 to liquid Ab_1An_1 we merely integrate this reaction over the temperature range 1500°–1450° and the composition range Ab_1An_9–Ab_1An_4. Thus we could start with a liquid of composition Ab_1An_5, permit it to crystallize until at 1500° the crystals would be of the composition Ab_1An_9, filter off the crystals, permit the liquid to cool to 1450°, when it would attain the composition Ab_1An_1, and then add the foreign crystals Ab_1An_9 that we filtered off. It is plain that we would have available by the making over of these crystals at 1450° all the heat that would have been evolved between 1500° and 1450° by the continuous process of making over of these crystals had they been left in contact with the liquid. Though we have used the plagioclase series as an illustration it is clear that the exothermic reaction taking place at 1450° is merely a deferred result of the principle of Le Chatelier which states that an equilibrium reaction proceeds, with falling temperature, in the direction resulting in evolution of heat. It is a perfectly general property of any solid solution series that if, at any temperature, crystals which are at equilibrium with liquid at a higher temperature are added to saturated liquid, the reaction which ensues between liquid and crystals is exothermic.

The case of the addition of an inclusion of composition nearer the low temperature (more sodic) end of the solid solution series may now be examined. A liquid of composition Ab_1An_2 is just saturated at 1490°. We cannot add to it a more sodic solid inclusion at the same temperature because any more sodic inclusion will be liquid at this temperature. But if we add inclusions of Ab_2An_1 at such a temperature that they are solid, say 1200°, it is plain that the actual temperature of the liquid is adequate to melt these inclusions; the only question is the source of the quantity of heat. The liquid must, of course, be cooled off in supplying the heat required to heat up the inclusions, but, since the liquid is saturated, it cannot be cooled without some crystallization taking place. However, it will take a very small amount of crystallization to supply the heat necessary to heat up a considerable amount of inclusions. The enormous discrepancy between the specific heats of silicates and their solution heats is plainly of double significance in connection with these problems. Not only can the heat necessary to heat up the inclusions be supplied by crystallization of some of the liquid, but so also can the heat required to melt the inclusions. To accomplish this it will require, however, the formation of crystals approximately equal in amount to the amount of inclusions melted. If we added 20 per cent of inclusions of Ab_2An_1 at 1200°, to a liquid of composition Ab_1An_2 at 1490° we would obtain (assuming that these thermal adjustments took place very rapidly compared with concentration adjustments) a mass of liquid about (Ab_2An_3) containing in it about 20 per cent of crystals of the kind in equilibrium with it (about Ab_1An_5) and containing also the inclusions converted to liquid, the whole at a temperature of about 1470°. There is no objection, therefore, to the conversion of an inclusion into liquid if the inclusion is sufficiently contrasted with the magma in composition in the proper direction; nor is such melting of an inclusion to be regarded as evidence of superheat in the magma.

This condition, in which liquid inclusions are contained in the magma, is of course a temporary one and it is rather the end result that has particular significance in petrogenesis. Final adjustment of concentration takes place by formation of a single homogeneous liquid and adjustment of the composition of the crystals to that in equilibrium with this liquid. This necessitates a further drop in temperature to about 1460° where the whole mass consists of the liquid $Ab_{45}An_{55}$ containing somewhat less than 20 per cent crystals of the composition about Ab_1An_4. Thus the net result of the addition of inclusions of composition more sodic than the liquid is that the inclusions become a part of the liquid and at the same time calcic crystals are formed in amount slightly less than the amount of inclusions added, the heat needed in order to make the inclusions part of the liquid being supplied by the formation of crystals. In the sense that they become a part of the liquid the inclusions are dissolved, but the process is not simply the formation of a liquid whose composition is the sum of that of the magma and the inclusions.

Let us now observe how these effects are carried over into more complex systems. Figure 6 is the equilibrium diagram of the system diopside: anorthite: albite for which we have discussed the heat quantities on an earlier page and found that the solution heat of any solid phase can be regarded as substantially equal to its latent heat of melting. A liquid of composition *A* is, at 1250°, just saturated with plagioclase of composition Ab_1An_4 approximately. If foreign inclusions consisting of the plagioclase Ab_1An_9 were added to this liquid we would have an effect strictly analogous to that described for simple plagioclase mixtures. The liquid would tend to make the inclusions over into Ab_1An_4 which takes place with evolution of heat.

If the rate of withdrawal of heat were very slow this reaction might result in an actual rise of temperature and the establishment of equilibrium at the higher temperature where the plagioclase crystals would be slightly more calcic than Ab_1An_4. If the liquid *A* had come into being as a result of the partial crystallization of another liquid, and if it carried plagioclase crystals suspended in it that showed zoning, the addition of the foreign inclusions mentioned might therefore result in a reversal of the zoning.

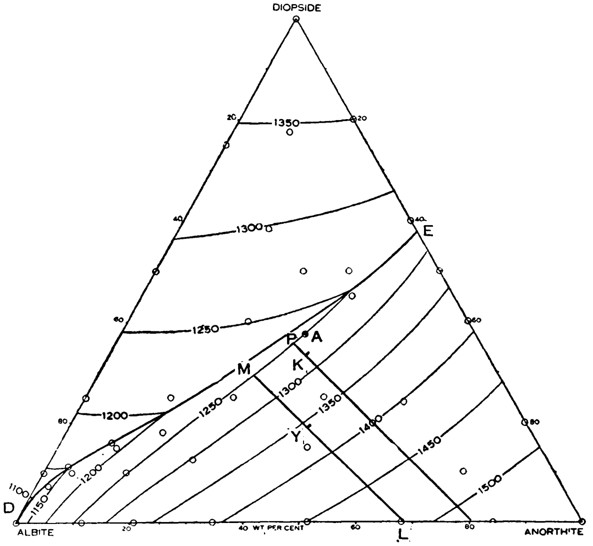

FIG. 6.—Equilibrium diagram of diopside, anorthite, and albite

The "attack" of the liquid upon the inclusions would be facilitated at the margins and along any channels where the inclusion happened to be more readily penetrated. The replacement of a small unit of Ab_1An_9 by Ab_1An_4 means a large local increase of volume so that the action is bound to have a disintegrating effect upon an inclusion suspended in liquid. Thus the material of the inclusion, as it is gradually made over, tends to become strewn about in the surrounding liquid but there is no actual solution, no increase in the amount of liquid—indeed, there is a diminution. Such should be the behavior of an inclusion richer in calcic plagioclase than the crystals with which the liquid was in equilibrium. At a later point in the paper it will be shown that the observations of many petrographers upon actual rock inclusions strongly suggest just such an action.

If we turn now to inclusions of plagioclase less calcic than the crystals with which the liquid is in equilibrium we find that quite a different condition obtains. We may begin with the liquid *A*, again at 1250°, and add to it foreign inclusions of Ab_1An_1 already heated to 1250°. It will be noted that we are adding plagioclase of the same composition as that in the liquid since liquid *A* is a mixture of Ab_1An_1 and diopside. Suppose that the reaction takes place at first between a thin layer of liquid adjacent to the inclusion and an equal weight of the peripheral part of the inclusion. The composition of this reacting mass is then to be represented by the point *Y*. Suppose further that the reacting mass is a very small portion of the total so that no significant drop of temperature occurs, for in this case the reaction absorbs heat. Equilibrium will be established in this reacting layer sensibly at 1250° when the composition of the crystalline outer crust of the inclusion is Ab_3An_7 (*L*) and that of the adjacent thin layer of liquid is *M*, which is a mixture of Ab_2An_1 and diopside. If the general cooling of the liquid were proceeding rapidly so that this condition were "frozen-in" we would have a central core of unaltered inclusion of composition Ab_1An_1, an altered crust of the inclusion of composition Ab_3An_7, a reaction rim (formerly liquid) about this, consisting of a mixture of diopside and Ab_2An_1, all surrounded by the main mass consisting of a mixture of diopside and Ab_1An_1. The reaction rim is not intermediate in composition between the inclusion and the main mass, nor yet between the altered crust of the inclusion and the main mass. This is a commonly observed feature of reaction rims and has been referred to "selective diffusion," an explanation which is correct but rather misleading. The effect is really due to equilibrium effects between the inclusion and the liquid and such diffusion as occurs is selective only because equilibrium selects certain constituents to become part of the liquid and others to be fixed in the solid phase. In the case we have described, more sodic plagioclase is emphasized in the new liquid formed and more calcic plagioclase is emphasized in the solid product. We shall find it to be a general result of reactions of this kind that the liquid should be enriched in the constituents toward the low temperature end of a solid solution series and the solid in those toward the high temperature end.

We have seen, then, that even when we add inclusions of a plagioclase of the same composition as the plagioclase existing as liquid in the magma, quite marked reaction effects may be found.

Let us now examine the same example but make the cooling of the liquid very slow. In other words, we shall discuss the end result of the action described above, which gives a reaction rim only as a temporary condition. In this case we shall imagine that the liquid formed about the inclusion becomes a part of the main mass of liquid as a result of diffusion and convection, and also that the solid products of the reaction become distributed through the liquid upon disintegration of the inclusion, due to the formation of local pockets of liquid and to the volume changes taking place in the change of composition of the solid phase. Thus the inclusion completely disappears as a distinct entity. Let us imagine that the amount of the inclusions was 10 per cent of the total and determine what the effect on the mass as a whole will be. The bulk composition of the mass is represented by the point *K* and if the temperature were maintained at 1250° the inclusions, formerly Ab_1An_1, would be changed to crystals of a composition close to Ab_1An_4 and the liquid would acquire the composition *P*. The crystals would amount to only about 6 per cent of the mass and to maintain the temperature constant would require addition of heat. If the only heat available were that of the mass itself its temperature would be lowered and a slightly greater amount of crystals formed. The net result would be, however, a marked change in the composition of the inclusions, a moderate decrease in the actual amount of solid material with corresponding increase in the amount of liquid. The liquid, too, becomes more albitic, that is, is pushed onward upon its normal crystallization course.

If, instead of inclusions of Ab_1An_1, more sodic inclusions were added, say Ab_2An_1, there would be a somewhat greater increase in the amount of liquid and a markedly greater enrichment of the liquid in more albitic plagioclase. Inclusions as rich in albite as $Ab_{10}An_1$ might be completely melted by the liquid before becoming a part of the general liquid, their melting being accomplished by precipitation of more basic plagioclase.

Summing up the result of adding to a liquid various members of a solid solution series with which it is saturated we find that if the added inclusion is nearer the high temperature end of the series than the crystals with which the liquid is saturated the reaction is such as to decrease the amount of liquid and is exothermic. If the inclusion is nearer the low-temperature end of the series than the crystals with which the liquid is saturated, the reaction is such as to increase slightly the amount of liquid and is endothermic. The liquid, too, is enriched in this case in the constituents of the low-temperature end of the crystallization series. Even inclusions consisting of the precise crystals with which the liquid is in equilibrium must react with the liquid as the temperature falls.

Whatever the composition of the inclusions, then, the liquid may show very marked effects upon them even though it is saturated, and consequently such effects would not constitute evidence of superheat. A little consideration will show, too, that these reactions have no significant effect upon the course of the liquid. Regarding the progress of the liquid as resulting from fractional crystallization, the liquid will in all cases run along the boundary curve (*ED*) as the temperature falls. The point it will eventually reach on this curve will depend upon the perfection of fractionation which in turn depends upon the rate of cooling. Inclusions of the more calcic kind tend to limit the career of the liquid by using it up, but at the same time furnish heat that tends to slow up the rate of cooling. Inclusions of the more sodic kind tend to push the liquid onward upon its course of crystallization, but hasten the cooling. The original unaffected liquid has all the differentiation potentialities that the liquid has after entering into the reactions mentioned.

REACTION SERIES

In the discussion relative to liquids of the diopside:anorthite:albite system nothing has been said regarding the effect of adding solid diopside to liquids saturated with diopside for the reason that there is no effect. The solid diopside simply remains as such on account of its being a pure compound of definite composition. But rock-forming minerals are seldom so simple. Quartz is the only important example of a rock mineral of definite composition, practically all others being of a variable nature, that is, solid solutions. The rock-forming pyroxenes do not fall behind in this respect and the addition of pyroxene to a natural magma saturated with pyroxene would in general be attended by reaction phenomena similar to those we have described for the plagioclases. The precise nature of the reactions in the case of the pyroxenes cannot be stated except for the clino-enstatite-diopside solid solution series.[1]

In another paper the writer has discussed solid solution series and offered reasons for calling them *continuous reaction series*. The importance of the reaction relation between liquid and crystals was there discussed in its bearing on crystallization. Here we have seen its importance in connection with the behavior of inclusions.

As was pointed out in the paper referred to, there is another type of reaction relation between liquid and crystals that is exhibited in the *reaction pair* and the *discontinuous reaction series*.[2]

The existence of such series is again of great significance in connection with the behavior of inclusions. An important reaction pair are the olivine, forsterite, and the pyroxene, clino-enstatite. Their relation is exhibited in its simplest form in the binary system, forsterite-silica, of which the equilibrium diagram is shown in Figure 7. The effect of adding crystals of the first member of a reaction pair to a liquid saturated with the second member is well illustrated by this system. A liquid of composition (*M*) is saturated with clino-enstatite but lies on the unsaturated side of the metastable prolongation of the forsterite liquidus. It is therefore unsaturated with forsterite and we may imagine that around each added forsterite crystal a small quantity of liquid of composition (*N*) may form. This condition is, however, metastable and from this liquid clino-enstatite would immediately be precipitated with formation of the liquid (*M*). Through constant repetition of this formation from forsterite of an infinitesimal quantity of the metastable liquid, with immediate precipitation of clino-enstatite, the forsterite is converted into clino-enstatite. Effectively, then, the liquid (*M*) is supersaturated with forsterite. It cannot dissolve forsterite but can only convert it into clino-enstatite, the phase with which it is saturated. This principle is capable of general application and we may state that a liquid saturated with any member of a discontinuous reaction series is *effectively* supersaturated with all higher members of the series; it cannot dissolve them but can only convert them into the phase with which it is saturated.

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[1] N. L. Bowen, *Amer. Jour. Sci.*, Vol. XXXVIII (1914), pp. 228–37.

[2] "The Reaction Principle in Petrogenesis," *Jour. Geol.*, Vol. XXX (1922), pp. 177–98.

In connection with the specific case we have discussed, it should be noted that the amount of clino-enstatite formed is not simply the chemical equivalent of the forsterite changed. The chemical equivalent would be somewhat less than one and one-half times the forsterite, whereas the amount of clino-enstatite formed is much greater, being in fact about five times the amount of forsterite. In other words, the action is not simply an addition of silica to the forsterite, with consequent impoverishment of the liquid in silica, for the liquid cannot have silica subtracted from it without passing under the clino-enstatite saturation curve, that is, without precipitating clino-enstatite. In order to convert the forsterite inclusions into clinoenstatite, the liquid must precipitate a large amount of clino-enstatite from its own substance, and the action uses up a large amount of the liquid. The liquid left has, however, in this binary case, the same composition as the initial liquid, if the temperature is kept

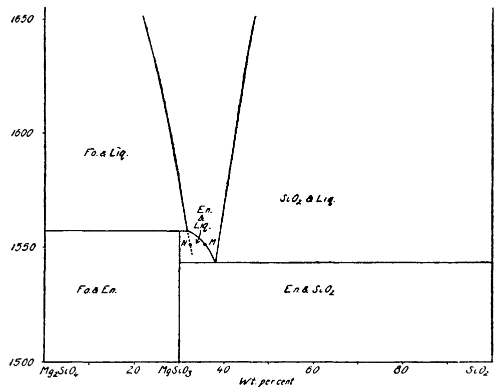

FIG. 7.—Lower temperature portion of the equilibrium diagram, forsterite-silica

constant. The liquid is not at all desilicated, even though it has caused the conversion of the inclusions into a more siliceous phase. By precipitation of the phase with which it is saturated, it has adjusted its composition in such a way as to remain on the same saturation curve. This again is a principle that can be applied in general to the reaction between a liquid and inclusions belonging at an earlier stage of the reaction series than the phase with which the liquid is saturated.

Further considerations relative to this reaction pair will be developed in connection with their behavior in the more complex liquids containing anorthite as worked out by Andersen[1] and shown in Figure 8. From this figure we may very readily predict what would happen to "inclusions" of the various solid phases immersed in liquid. Let us take first a liquid just saturated with forsterite (say *M* at 1450°). Ordinarily crystals of forsterite would separate first; they would then react with liquid to form pyroxene; pyroxene would continue to separate for a time and would then be joined by silica; finally, at the ternary eutectic 1222°, anorthite would join these, and the product would consist of pyroxene, silica, and anorthite. If to the original liquid some "foreign inclusions" of forsterite were added the liquid would, on cooling, attempt to make the forsterite over into pyroxene, but now there would not be enough liquid to accomplish this entirely, and it would be used up at 1260° while there was still some forsterite left; so that the solidified mass would now consist of pyroxene, forsterite, and anorthite. Thus we see that even though it is precisely the substance with which the liquid is in equilibrium, the addition of forsterite has a considerable effect upon the crystalline product formed. The exact effect is a tendency to limit the scope of the products to the early members of the crystallization sequence. In this case, silica, a later member of the sequence, does not appear. It is plain, too, that the effect does not depend on the particular properties of this reaction pair and that we may conclude that it would be true of any discontinuous reaction series. We have already seen that the same effect is found in the continuous reaction series (solid solution series). We may state it as a general law therefore that a saturated liquid in any system dominated by reaction series will not remain indifferent to inclusions even of the exact composition with which it is in equilibrium, and that the effect of the addition of such inclusions is a tendency to limit the scope of the crystalline products to adjacent members of the reaction series involved.

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[1] The system anorthite-forsterite-silica, *Amer. Jour. Sci.*, Vol. XXXIX (1915), p. 440.

Let us now examine what happens when inclusions of an early member of a discontinuous reaction series (or reaction pair) are added

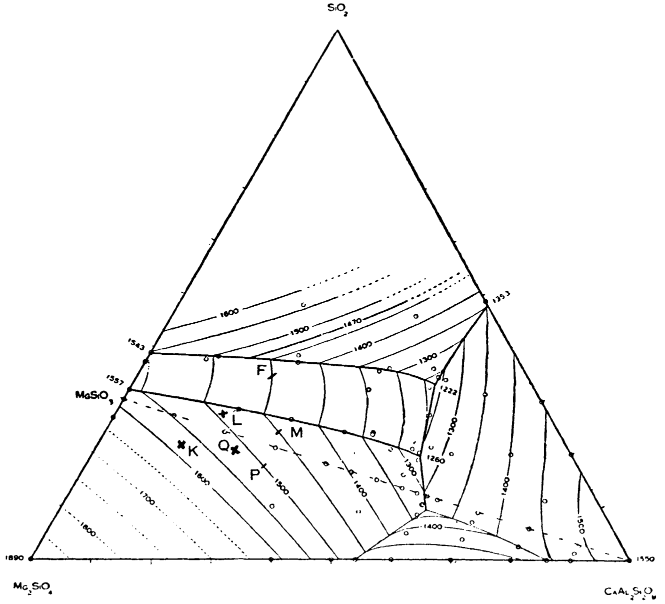

FIG. 8.—Equilibrium diagram of the system anorthite-forsterite-silica. (After Andersen.)

to a liquid saturated with a later member. The liquid *F* is just saturated with clino-enstatite at 1450°. If it is cooled, clino-enstatite will separate first, it will later be joined by silica and then by anorthite, when the whole mass will solidify at 1222°. But if inclusions of forsterite are added to this liquid it will instantly start to react with these inclusions and make them into the mineral with which it is saturated, viz., clino-enstatite. If there is perfect opportunity for reaction we may readily predict what the end result will be for varying amounts of added inclusions.

Suppose first that the amount of inclusions was such as to give a total composition represented by the point *K*. The liquid would then be completely used up by the reaction while some inclusions yet remained, so that the finally solidified mass would consist of forsterite, clino-enstatite, and anorthite. If, on the other hand, the amount of inclusions was such as to give a total composition represented by the point *L*, all the inclusions would be changed to clino-enstatite while some liquid yet remained, and this liquid would then pass onward to the deposition of silica and anorthite in the ordinary way. Thus the addition of inclusions of this kind, if in sufficient quantity, restricts the career of the liquid and confines the crystalline products to adjacent members of the reaction series.

It is perhaps not necessary to add that if the liquid did not react with the inclusions no effect on the course of the liquid would ensue.

Just as was the case in the binary system, the liquid is not desilicated by this addition of silica to the forsterite inclusion, but by precipitating an appropriate amount of the phase with which it is saturated (clino-enstatite), it maintains its position on the same (clino-enstatite) saturation surface.

Nothing has been said of the heat effect of this reaction and it has been tacitly assumed that the temperature remains constant. The reaction is, in fact, exothermic, as can be readily shown by applying the same reasoning as was applied to the similar case in a continuous reaction series. If no heat were abstracted from the system it would heat itself up and equilibrium would be established at a slightly higher temperature with a somewhat more magnesian liquid than the initial liquid. But the formation of this somewhat more magnesian liquid is not properly to be taken as an indication that the net result of the process is a direct solution of some of the inclusions. A direct solution of inclusions would mean a decrease in total solids and an increase in liquid, whereas the reaction referred to results in a diminution in the amount of liquid and a corresponding increase in the amount of solids even when this heating effect takes place. If heat is being taken from the system this process would act as a deterrent upon the rate of cooling.

All of these effects we have found to be true of analogous inclusions in the case of the continuous reaction series.

There is yet to be examined the example in which a late member of a discontinuous reaction series is added to a liquid saturated with an early member. To the liquid *P* at 1500°, where it is just saturated with forsterite, inclusions of clino-enstatite are added in an amount sufficient to give a total composition *Q* (about 20 per cent). If the temperature were kept constant equilibrium would be established when the mass consisted of 4 per cent forsterite and 96 per cent liquid, that is, the inclusions have been changed into the phase with which the liquid is saturated and there has been an increase in the amount of liquid. In order to effect this change heat would have to be added to the system. If the system is self-contained, that is, if the only heat available is the heat of the system itself, a cooling would result and this would necessitate the crystallization of a further amount of forsterite until the necessary heat was supplied by this crystallization and the cooling of the mass. The net result would depend entirely on the relative heats of solution of forsterite and clino-enstatite in the liquid. These are probably of the same order of magnitude, so that equilibrium would be established at about 1475° when the mass consisted of 10 per cent forsterite and 90 per cent liquid approximately. The net result, then, has been the conversion of the inclusions added (clino-enstatite) into the phase with which the liquid is saturated (forsterite), an enrichment of the liquid in the material added, with, at the same time, a pushing onward of the liquid along its usual course of crystallization. Or it could be stated that the inclusions pass into solution by precipitating their heat equivalent of the phase with which the liquid is saturated.[1] This, then, is the result of adding inclusions which belong to a discontinuous reaction series and are later in that series than the phase with which the liquid is saturated. It is sensibly the same result as that obtained in the corresponding case in the continuous reaction series.

EFFECTS OF MAGMA UPON INCLUSIONS OF IGNEOUS ORIGIN

In the paper in which the conception of the reaction series was developed it was shown that these series are very prominent in rocks. An attempt was made there to arrange the minerals of rocks as reaction series and it was found that there are, toward the basic end of rock series, two fairly distinct reaction series that finally merge into one in the more acid rocks. This was expressed diagrammatically as follows.

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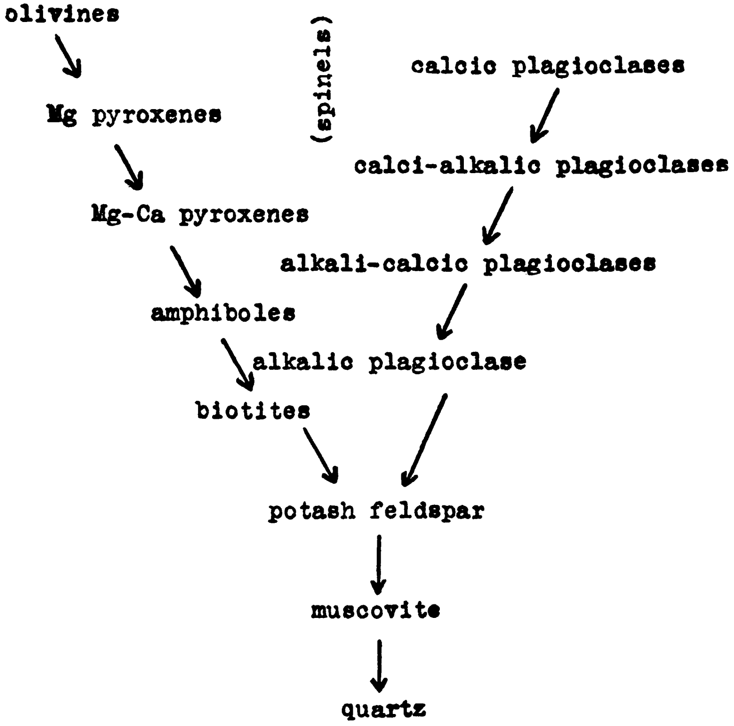
[1] This is only approximately true, for equilibrium is always established at a somewhat lower temperature and the cooling of the mass supplies a little of the heat.

TABLE II



On the basis of the principles that we have found to govern the behavior of inclusions belonging to reaction series we may deduce with considerable confidence the effects of liquid upon inclusions in this more complex series.

It may be stated immediately that any magma will tend to make inclusions over into the phase or phases with which it is saturated, in so far as the composition of the inclusions will permit. It may be stated also that any magma saturated with a certain member of a reaction series is effectively supersaturated with all higher members of that reaction series. It cannot, in any sense, dissolve inclusions of such higher members but can only react with them to convert them into that member of the reaction series with which it is saturated, often by passing through other members of the series as intermediate steps. The material used to effect these changes cannot be regarded as simply subtracted from the liquid for the liquid is not free to become impoverished in any random substance. In general impoverishment in any substance will cause the liquid to pass within a region of saturation and induce the precipitation of some of the phases with which the liquid is saturated.

Let us take, for example, a magma saturated with biotite, say, a granitic magma. This magma is effectively supersaturated with olivine, pyroxene and amphibole and cannot dissolve them in spite of the marked contrast of composition, which is often supposed to be an aid to the solution of inclusions. But the magma can and will react with these minerals and convert them into biotite, usually by steps. The subtraction of material necessary to produce biotite will cause the precipitation of the minerals with which the magma is saturated until either the liquid or the inclusions are used up or the reaction is brought to an end on account of mechanical obstruction.

Similarly, granitic magma saturated with an acidic plagioclase cannot dissolve basic plagioclase but can only react with it and convert it into more acid plagioclase.

These remarks are tantamount to the statement that saturated granitic magma cannot dissolve inclusions of more basic rocks. The magma will, however, react with the inclusions and effect changes in them which give them a mineral constitution similar to that of the granite. These changes will often be accompanied by disintegration of the inclusions and the strewing about of the products which may be indistinguishable from the ordinary constituents of the granite. The inclusions may thus become completely incorporated though not in any sense dissolved. It is this action of magmas upon inclusions that makes particularly difficult the problem of distinguishing xenolith from autolith, i.e., accidental inclusion from cognate inclusion.

Whatever origin one may assign to a granitic magma—let it be formed by differentiation of more basic magma, by differentiation of syntectic magma or by palingenesis of sediments—there seems no escape from the conclusion that it will normally be saturated. The normal effect of granite upon more basic inclusions should therefore be such as has been outlined above. Thus we find that Fenner, in describing the action of granitic magma on basic bands in an injection gneiss, says, "In other places the dark minerals appear to have been taken up or digested by the magma and to have crystallized out again in large blades. Even in the latter case it is not always certain that perfect solution has been effected at any one time. The process may have been rather in the nature of a chemical reaction with the original minerals or the solution and redeposition of a portion of the material at a time,[1] leaving the general relations undisturbed. This possibility is suggested by the fact that frequently even the coarser micaceous blades or aggregates of dark minerals show evidence of parallelism and this would be difficult to account for under the supposition that solution was so perfect that the original structure was completely wiped out."[2] Here, apparently, we have a good example of the transformation, by reaction rather than solution, of the dark bands into mica-rich material, mica being the dark mineral with which the magma is saturated. The change of serpentine into biotite as observed by Gordon at the borders of granitic pegmatites is precisely the action to be expected.[3]

V. M. Goldschmidt describes the strewing about of the minerals of a basic hornfels in magmas of the Christiania region. He says, "This strewing about hardly has its origin in a solution of the minerals and their later separation. Had solution occurred the grains would not have retained their original forms and they would have differed in composition from the minerals of the hornfels." Near the border of an apophysis of the nordmarkite, grains of diopside from the hornfels are surrounded by a rim of aegirite. In the center of the apophysis the aegirite has no core of diopside.[4]

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[1] Note discussion on p. 532.

[2] C. N. Fenner, "The Mode of Formation of Certain Gneisses in the Highlands of New Jersey," *Jour. Geol.*, Vol. XXII (1914), pp. 602–3.

[3] "Desilicated Granite Pegmatites," *Proc. Acad. Nat. Sci. Phila.*, Part I (1921), p. 169.

[4] V. M. Goldschmidt, "Die Kontaktmetamorphose im Kristianiagebiet," *Vid. Selsk. Skr. I. Mat. Naturv. Klasse* (1911), No. 1, pp. 107–8.

In the foregoing discussion granitic magma has been taken merely as an example to which the principles developed may be applied. As a further example it may be pointed out that saturated dioritic magma cannot dissolve inclusions of gabbro, peridotite or pyroxenite but, given the opportunity, it will react with those inclusions and convert them into the hornblende and the plagioclase with which it is saturated, at the same time precipitating a further amount of this hornblende and plagioclase from its own substance.

These are but examples of the application of the principle that a saturated magma cannot dissolve inclusions of material farther back in the reaction series (in general more basic) than the crystals with which it is saturated. At the same time the magma can attack these inclusions, reacting with them in such a manner as to convert them into the crystals with which it is saturated.

The dioritic magma we have considered will not remain indifferent to inclusions even of the exact composition of the crystals with which it is in equilibrium, for as the temperature falls it will modify the composition of these inclusions just as it modifies the composition of its own crystals. Indeed this case may be regarded as a special case of that just discussed, for, as the temperature falls, the composition of the liquid changes, and the inclusions then pass into the class of those considered above.

We now come to the case of inclusions of material later in the reaction series than the crystals with which the liquid is saturated. It should be noted that this includes masses of rock of the same composition as the liquid itself, for example its own chilled border phase.

Saturated basaltic magma can react with inclusions of igneous rocks later in the reaction series (in general more acid) in such a way that the inclusions become part of the liquid, crystals of the phases with which the basalt is saturated being precipitated at the same time. If these crystals are removed by gravity or otherwise the action on the inclusions may continue, the liquid changing in composition toward the composition of the inclusions and precipitating later and later members of the reaction series until finally it is saturated with precisely the crystalline phases contained in the inclusions. If granitic inclusions, say, were available at the upper contact of a mass of basaltic magma, they would be attacked by the magma in the manner noted and, in a lower layer, accumulation of the precipitated products of the reaction would take place. These would be the early crystals formed in basaltic magma. The upper liquid is thus gradually changed in composition and the crystals precipitated from it are successively later and later members of the reaction series. Attack upon the inclusions continues until finally the upper liquid becomes granitic. All of this depends on a rate of cooling slow enough for free crystal settling to occur. But if the cooling is sufficiently slow for crystal settling all of these results could accrue from the simple differentiation of the basaltic magma. Indeed the principles developed show that the inclusions can become part of the liquid only when they have a composition toward which the composition of the liquid can vary by spontaneous differentiation.

Nevertheless it is apparent that the amount of granitic differentiate might be greatly augmented by this action. It may safely be assumed therefore that in many individual cases considerable quantitative importance in the production of a granitic differentiate of basic magma is to be assigned to the action noted. It is a sort of solution of granitic inclusions though not a simple, direct solution and is in no sense essential to the production of a granitic differentiate.

Daly is of the opinion that many granites are secondary, that is, are formed by solution of granite in basaltic magma and subsequent differentiation.[1] It is seen from the above that theoretical considerations support belief in a process which, in its results at least, is practically that advocated by Daly. The process itself he considers to be rather a simple solution of granite in superheated basaltic magma. We have seen that no superheat is necessary to produce solution by a sort of reactive process. Moreover, we have seen that the incorporated granitic material is to be regarded rather as a contribution to the normal granitic differentiate. There appears, however, to be no reason to doubt that, at times, this contribution might equal or possibly even exceed in amount the granitic differentiate capable of formation from the uncontaminated magma.

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[1] Indeed, Daly derives in this manner all granites except a supposed original granitic shell of the earth (*Igneous Rocks and Their Origin*, p. 323).

The limiting factors are principally mechanical rather than thermal or chemical and are very difficult to evaluate. It should be noted, in particular, that the combination which is most favorable for significant effects in the way of reactive solution, viz., decidedly acid inclusions and decidedly basic magma, is unfavorable in another respect. The inclusions will be lighter than the magma and will not tend to sink in it, whereas it is the sinking of inclusions through the magma which favors particularly notable reaction effects since it continually brings new magma into contact with the inclusions.

As an example of the effect of basic magma on more acid igneous inclusions basaltic magma and granitic inclusions have been taken. Between such extremes the more marked effects should be obtained, but it cannot be doubled that any basic magma can dissolve, by the same reactive process, inclusions of a rock later in the reaction (crystallization) series. Direct melting of granitic inclusions to masses of liquid by basaltic magma is not ordinarily to be expected because the solid granite does not retain the volatile components that aid in lowering the melting temperature of granitic magma below that of basaltic magma. This lack is no bar to the reactive solution process described, though it may limit it somewhat.

EFFECTS OF MAGMA ON INCLUSIONS OF SEDIMENTARY ORIGIN

The general problem of the effects of magma upon inclusions of sedimentary origin is much more difficult than the similar problem in connection with igneous inclusions. Sedimentary rocks have their compositions determined by processes wholly independent of igneous action and do not correspond in composition with the products precipitated from magmas at any stage of their career, that is, cannot be placed definitely in the reaction series. However, certain minerals that can be formed in magmas do occur in the sedimentary rocks and often the composition of a sediment is such that by mere heating it can be transformed into an aggregate made up exclusively or almost exclusively of igneous rock minerals. Again sediments exhibit extremes of composition, being very rich in calcium carbonate, aluminum silicate or silica itself, and these present a special problem. Yet it is perhaps not generally realized how much even of these extreme sediments might be incorporated in an igneous rock without changing its mineralogy. The fact is an obvious deduction from the equilibrium diagram of any investigated three component system and it is equally true of a more complex system. Figure 9 shows the solid phases formed immediately upon complete consolidation of any mixture of CaO, Al_2O_3 and SiO_2. A mixture of composition (*A*) consists, upon complete consolidation, of anorthite, wollastonite, and gehlenite, one third of each. One may

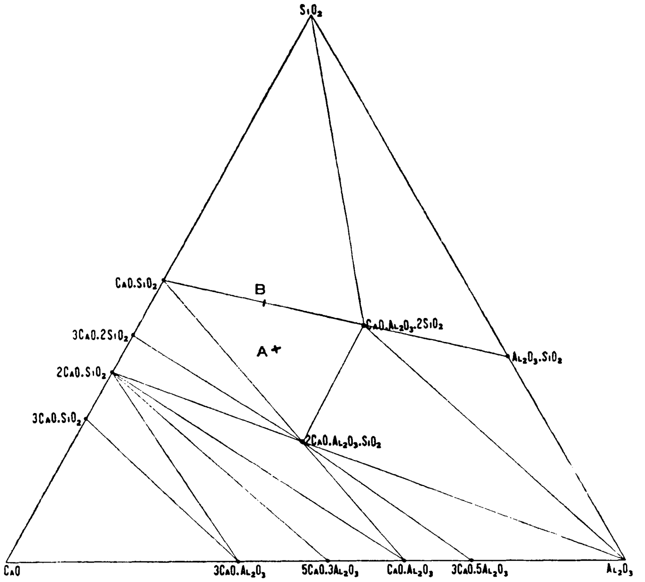

FIG. 9.—Diagram of the system CaO-Al_2O_3-SiO_2 showing phases formed upon complete consolidation. (After Rankin and Wright.)

add to this mixture any amount of CaO up to about 15 per cent of itself, without changing the mineral composition of the consolidated product. Similar amounts of either Al_2O_3 or SiO_2 might be added, the only change in all cases being in the relative amounts of the minerals, not in the kind of minerals. A certain amount of change in the order of separation of the minerals would be effected but the temperature of final consolidation, the composition of the final liquid and the possible differentiates that might be formed by fractional crystallization would in all cases remain as before. Only when amounts are added in excess of those mentioned will a new crystalline phase appear and new fractionation possibilities enter.

There are, however, certain mixtures in the system that will immediately present a new phase upon addition of the slightest amount of CaO, Al_2O_3, or SiO_2. Such is the mixture (*B*) which consists on consolidation of anorthite and wollastonite, one half of each. The addition of either CaO or Al_2O_3 will bring in the new phase, gehlenite, and of SiO_2 the new phase, tridymite, and each will change the course of crystallization. This is because the composition chosen is a limiting case in the ternary system and is in reality of only two components; and the addition of, say, lime carries it out of the two component system. It will be noted that the mixture considered contains the three oxides, though of only two components, and on consolidation only two solid phases are formed. It might seem on first thought that this corresponds with the case of the natural magmas, for these usually form solid phases fewer in number than the oxides present. However, there is another factor, namely, solid solution, that may give rise to this peculiarity and we shall find that it is to solid solution that the limited number of phases formed from magmas is usually to be referred.

Let us now examine a ternary system of oxides that has been completely investigated and in which the factor of solid solution enters. Such is the system $CaO{:}MgO{:}SiO_2$ studied by Ferguson and Merwin.[1] A liquid of composition *A*, Figure 10, forms on complete consolidation just two solid phases, the olivine, forsterite, and clinopyroxene of composition between diopside and $MgSiO_3$. To this liquid any amount of calcite up to 12 per cent of its weight could be added without changing the mineralogy of the consolidated product. This would still consist of olivine and clinopyroxene but the pyroxene would be richer in CaO, that is, closer to diopside. Only an amount of calcite in excess of 12 per cent would bring in another phase, akermanite, together with the diopside and olivine. It is easy to see from an inspection of the figure that addition of dolomite would likewise have no effect on the kind of phases crystallizing unless more than about 16 per cent were added.

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[1] *Amer. Jour. Sci.*, Vol. XLVIII (1919), p. 109.

When we have spoken of adding calcite and dolomite to the mixtures mentioned we have imagined that the lime and magnesia have been taken into solution as they might be in a laboratory furnace where the furnace supplied the requisite quantity of heat. This quantity would be very large, for the conversion of carbonate into silicate is an endothermic reaction and its conversion into silicate in solution is undoubtedly still more strongly endothermic. Now if the liquid were originally a saturated liquid and calcite or dolomite were added without any provision for additional heat other than that already contained in the liquid, the lime and magnesia would not be simply dissolved. Instead, precipitation of olivine (forsterite) would occur, no matter whether calcite or dolomite was added, and as the forsterite separated the liquid would attack the calcite, converting it into lime silicates. Since this is an endothermic reaction the heat for it can be supplied only by crystallization of something from the liquid which will be, of course, the phase with which it is saturated, viz., forsterite. There is another

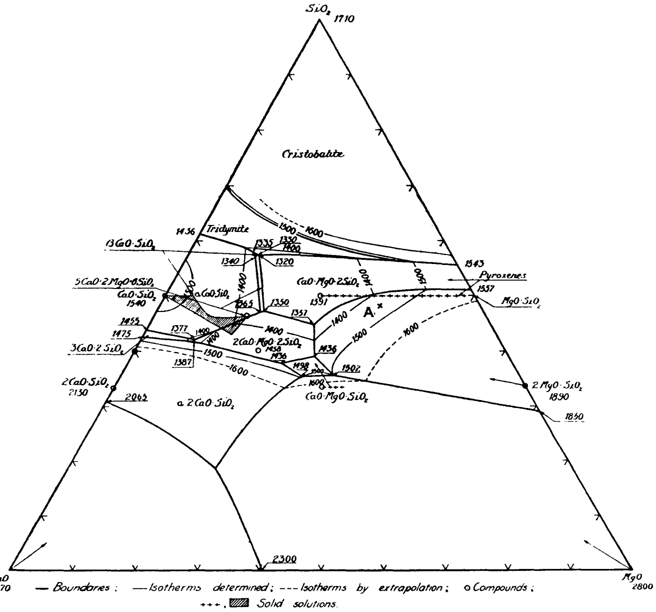

FIG. 10.—Equilibrium diagram of the system CaO-MgO-SiO$_2$. (After Ferguson and Merwin.)

reason why forsterite is precipitated for the formation of lime silicates requires some silica but the liquid cannot be desilicated since it lies on the forsterite saturation surface. Therefore the liquid changes its composition by moving on the forsterite surface toward lower temperature. It does not move directly away from forsterite, however, but curves somewhat in the direction of the composition of the inclusions. If the reaction with the inclusions is strongly endothermic, as it is in this case, the liquid would move down to the forsterite-pyroxene boundary curve where separation of pyroxene would occur and the liquid would be entirely used up without ever getting over to such compositions that akermanite would separate from it. However, some part of the inclusions might have been converted to akermanite. Thus, however large a supply of inclusions were available, even in excess of the 12 per cent mentioned above, the liquid might never get over to such compositions that any new phase is precipitated from it, but would precipitate only forsterite and pyroxene as in normal crystallization, with, however, a certain increase in the lime content of the pyroxene.

These considerations lead us to the conclusion that the liquid we have chosen, even if it has a moderate amount of superheat and therefore is capable of directly dissolving a little lime and magnesia from calcite or dolomite, does not suffer a change in the kind of solid phases capable of forming from it. There results only a modification of the composition of the phase of variable composition (pyroxene). And, as a consequence of the heat effect of the solution of inclusions, saturation shortly ensues and thereafter further action upon the inclusions is accomplished only with concomitant precipitation of the phase or phases with which the liquid is saturated, whereby the liquid is constrained to follow a general course not significantly different from the one it would follow were no inclusions present.

The results obtained in the foregoing enable us to draw certain conclusions as to the effects of natural magmas upon inclusions of various sedimentary rocks. One point that does not seem to be realized is that when a sedimentary inclusion becomes immersed in a magma nothing is added that the magma does not already contain. Both belong to the same polycomponent system embracing all the rock-forming oxides. Obviously the effects of all possible sediments cannot be examined, but our purpose will be served if we take the most extreme departure from igneous composition. As representative of this condition, for quartzite we may imagine the addition of pure quartz; for limestone, of pure calcium carbonate; and for shale, of pure kaolin. Any actual sediment would usually contain all of these, together with other constituents that lessen its departure from igneous composition.

Let us take a magma of basaltic composition which, on crystallization with comparatively rapid cooling, would form mainly plagioclase, and clinopyroxene, with some olivine, a little ore mineral and possibly some orthopyroxene. All of these are minerals of variable composition; some of them, in particular the pyroxene, vary with respect to several components and to this is to be attributed the fact that the number of solid phases formed is less than the number of oxides present. This fact permits particularly wide adjustments in the composition of the solid phases without the appearance of new ones. Such basaltic magma, with a little superheat, could directly dissolve a moderate amount of sediments, yet even if these were of extreme composition the magma would crystallize with the production of the same solid phases as those mentioned above if crystallized under the same conditions.

Normally only saturated magma would be available and the superheated magma mentioned above would rapidly become saturated as a result of solution of inclusions. For the case of such saturated magma it may be stated as a first principle that the sediment would, in so far as its composition permitted, tend to be converted into the phases with which the magma is saturated. And the material necessary for such changes in the sediment would not be merely subtracted from the liquid but adjustments of the composition of the liquid would occur through separation of further amounts of the phases with which the liquid is saturated.

The precise changes in the composition of the solid phases formed cannot be represented graphically on account of the number of components involved, but equations can be written that afford a generalized conception of the possible adjustments for the addition of calcite, silica, and kaolin respectively.

The phases capable of formation from the original unchanged magma are:

Phase	Mineral molecules represented
Olivine	$Mg_2SiO_4+Fe_2SiO_4$
Magnetite	$FeO.Fe_2O_3$
Plagioclase	$CaAl_2Si_2O_8+$etc.
Pyroxene	$CaMgSi_2O_6+MgSiO_3+Al_2O_3$*$+CaFeSi_2O_6+$ $FeSiO_3+Fe_2O_3$*

Upon addition of CaO the following principal adjustments in the proportions of these mineral molecules may occur without the appearance of new phases:

$$CaO+2FeSiO_3+Fe_2O_3=CaFeSi_2O_6+FeO.Fe_2O_3;$$
$$CaO+3MgSiO_3=CaMgSi_2O_6+Mg_2SiO_4;$$
$$CaO+Al_2O_3+4MgSiO_3=CaAl_2Si_2O_8+2Mg_2SiO_4.$$

Upon addition of SiO_2:

$$SiO_2+Mg_2SiO_4=2MgSiO_3;$$
$$SiO_2+Al_2O_3+CaMgSi_2O_6=CaAl_2Si_2O_8+MgSiO_3.$$

Upon addition of kaolin, which we may regard as $Al_2SiO_5+SiO_2$, with SiO_2 having the same effect as above:

$$Al_2SiO_5+CaMgSi_2O_6=CaAl_2Si_2O_8+MgSiO_3.$$

The results may be put in words by stating that addition of lime tends to increase the amount of magnetite and olivine, to make the pyroxene more nearly a pure diopside-hedenbergite and to increase the anorthite content of the plagioclase. The addition of silica tends to decrease the amount of olivine and to increase the magnesian content of the pyroxene and the anorthite content of the plagioclase. The addition of kaolin tends to increase the amount of magnesia in the pyroxene and of the anorthite in the plagioclase.

In the case of superheated magma the added material might be directly dissolved and upon solidification the adjustments noted would appear in the crystalline phases. In the case of saturated magma the phases noted would be developed by reaction with the added material and at the same time a further amount of them would be precipitated from the liquid. In neither case would the course of crystallization be fundamentally changed since crystallization produces only the same solid phases slightly modified in composition. If consolidation took place under conditions permitting fractionation by settling of crystals no fundamentally new differentiation potentialities would be introduced by the solution or reaction with foreign material that has been discussed. The magma thus modified could give a diorite-granodiorite-granite sequence, say, only if the original magma could also have done so under the same conditions. It is a question whether, in the case of unsaturated magma, it can be safely assumed that the degree of superheat may be such that an amount of material can be dissolved in excess of that which can be taken care of by the adjustments in composition of existent phases. If this is possible new phases will appear and the course of crystallization and differentiation might be fundamentally modified. In the case of added CaO, for example, the new phase melilite might appear and the differentiates formed might be fundamentally different; might be, say, certain alkaline types as Daly has postulated.

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* Often written as existing in the Tschermak molecule, for which there is no good reason. See Washington and Merwin, *Amer. Jour. Sci.*, Vol. III (1922), p. 121.

EFFECTS OF BASALTIC MAGMA ON ALUMINOUS SEDIMENTS

With this possible exception in the event of excessive superheat, the statement should hold that reaction with foreign material can produce no new differentiation potentialities in the magma. Yet it is certain that some lines of differentiation may be emphasized by such agency, that is, that certain types of differentiate should be quantitatively of greater importance. This we have found to be true of reaction of magma with previously solidified igneous material. Thus when basaltic magma reacts with granitic material the tendency is to increase the amount of granitic differentiate capable of forming from the basalt. The effect of reaction with aluminous sediments is of sufficient importance to justify further discussion at this point. The result has been shown to be the emphasizing of more magnesian pyroxene and of anorthite. Now under certain conditions, not well understood, magnesian pryoxene separates from magmas as a distinct phase, an orthopyroxene, and the addition of aluminous sediments should emphasize this tendency. The formation of norite and of pyroxenites characterized by orthopyroxene as differentiates from basaltic magma, may therefore be facilitated by reaction of such magma with aluminous sediments. A suggestion along similar lines has already been made by Evans.[1]

An example of the reaction of basic magma with aluminous sediments, in which the relations discussed seem particularly clear, is afforded by the so-called Cortlandt series.[2] The early work of Williams and the later work of Rogers on this series treats in some detail the features bearing upon the question here at issue.[3] The Cortlandt series is intrusive into the Manhattan schist (locally into other formations also) and the interaction between schist and magma is in places rather well displayed. The Manhattan schist is a metamorphosed sedimentary rock of the nature of a shale. Its composition, as given by a composite analysis of five specimens, is shown in Table III under I. No doubt it varies considerably from this average and is sometimes more aluminous, but it is always far from the composition of kaolin, which composition we have used

TABLE III

	I	II
SiO_2	57.94	40.16
Al_2O_3	21.70	29.50
Fe_2O_3	1.57	19.66
FeO	5.90	5.80
MgO	2.49	trace
CaO	.58	.85
Na_2O	1.74	1.46
K_2O	4.68	1.36
H_2O+	2.17	....
H_2O-	.29	....
TiO_2	1.01	....
MnO	.19	....
S	....	.82
	100.26	99.61

I. Manhattan schist. Composite analysis of five specimens beyond border of the Cortlandt series. Analyst, G. S. Rogers.

II. Manhattan schist on contact of Cortlandt series. Analyst, F. L. Nason in G. H. Williams, *Amer. Jour. Sci.* (3), Vol. XXXVI (1888), p. 259.

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[1] J. W. Evans in discussion of paper by C. E. Tilley, *Quar. Jour. Geol. Soc.*, Vol. LXXVII, p. 133.

[2] G. H. Williams, *Amer. Jour. Sci.* (3), Vol. XXXI (1886), p. 26; (3), Vol. XXXIII (1887), pp. 135, 191; (3), Vol. XXXV (1888), p. 438; (3), Vol. XXXV (1888), p. 254.

[3] G. S. Rogers, *Ann. N.Y. Acad. Sci.*, Vol. XXI (1911), pp. 11–86.

in discussing the effects of basic magma on aluminous sediments. This affords an opportunity of discussing the behavior of an actual example of aluminous sediment. The ordinary Manhattan schist is made up principally of the minerals quartz, biotite, muscovite, orthoclase and plagioclase. These are all minerals of ordinary igneous rocks, particularly of more "acid" types, and correspond to a rather low temperature equilibrium. A glance at the analysis shows, however, that the composition is far from that of an ordinary igneous rock, which means that the minerals are of somewhat different composition and are present in different proportions. Now we have found in our discussion of the reaction of any saturated magma upon igneous inclusions that if the inclusions belong to a later stage in the reaction series they may become a part of the liquid by causing the precipitation of the phases with which the liquid is saturated. Average Manhattan schist, since it consists of the minerals of an acidic igneous rock, may be regarded as consisting in part of material belonging to a later stage in the reaction series than basaltic magma, but since it does not correspond exactly with any such igneous mass it must be regarded as having a certain amount of surplus material in addition. If we imagine saturated basaltic magma reacting with inclusions or wall rock of schist we may expect the action to be selective. Such substances as may become a part of the liquid would be removed from inclusions or wall rock with corresponding enrichment in what has been called surplus material. The substances removed would be principally silica, alumina, alkalis and to a minor extent other oxides, all in the proportions in which they enter into some "acid" igneous rock. Our knowledge of the exact proportions may be thus indefinite and yet sufficient for a general solution of the problem. Comparison of the analysis of the Manhattan schist with those of acid igneous rocks gives us a good conception of what the surplus material will be. It will plainly be rich in alumina and iron. A certain stage of the reaction between magma and inclusions or wall rock should exhibit a mass rich in these oxides. This stage is abundantly represented in both wall rock and inclusions by richness in sillimanite, staurolite and other aluminous and ferrous minerals. Chemically it is shown by analysis II in Table III which represents wall rock at the margin of the intrusive.

The so-called surplus material does not remain indefinitely as such, but by the time we have obtained inclusions very rich in sillimanite a turning point in the process is reached. Hitherto certain constituents of the schist have become a part of the liquid in virtue of the precipitation of various phases with which the liquid (magma) was saturated. Now reactions between magma and inclusions become of such a nature that the precipitation of phases with which the magma is saturated is the sole process, these phases being appropriately modified by the inclusions. There is now no addition to the liquid. The exact modification of the phases that is produced by sillimanite has already been discussed and equations representing the changes have been written. The net result is an increase in the amount of anorthite and magnesian pyroxene at the expense of lime-bearing pyroxene, and this tends to promote the separation of magnesian pyroxene as a distinct phase, orthopyroxene. Thus the tendency of the magma to give a noritic differentiate is increased, as well as the likelihood of formation of a pyroxenite containing orthopyroxene. These expectations are well matched by the Cortlandt series.

Apart from possible later differentiation this production of norite and related types is the end result of the action of basic (basaltic) magma on sillimanite-rich inclusions. We may with profit examine the details of the action, that is, the processes going on within and immediately around the sillimanite-rich inclusions, immersed in a magma rich in plagioclase and pyroxene. This examination serves to throw some light on the detailed mineralogy of the inclusions, and in particular on the separation of free alumina, as corundum.

If a mass of sillimanite were added to some anorthite just above its melting point, it can be readily seen from examination of Figure 11 that some of the sillimanite would be converted into corundum. This is because the line joining sillimanite and anorthite passes through the corundum field. We may imagine, for example, that the bulk composition of a layer immediately surrounding the sillimanite is 50 per cent sillimanite and 50 per cent anorthite. The mixture represented by this layer, at 1550°, would consist of sillimanite, corundum, and liquid. If the original anorthite liquid had an excess of silica amounting to about 10 per cent, no corundum would be formed from sillimanite, because the join of sillimanite with such a composition misses the corundum field. Plainly the freeing of corundum from sillimanite depends in these liquids on the liquid being "basic," that is, having not more than a moderate excess of silica over the feldspar composition. Free silica associated with the sillimanite does not have a comparable effect in restricting the formation of corundum; indeed, the silica would require to be nearly equal in amount to the sillimanite in order to neutralize the tendency to form corundum.

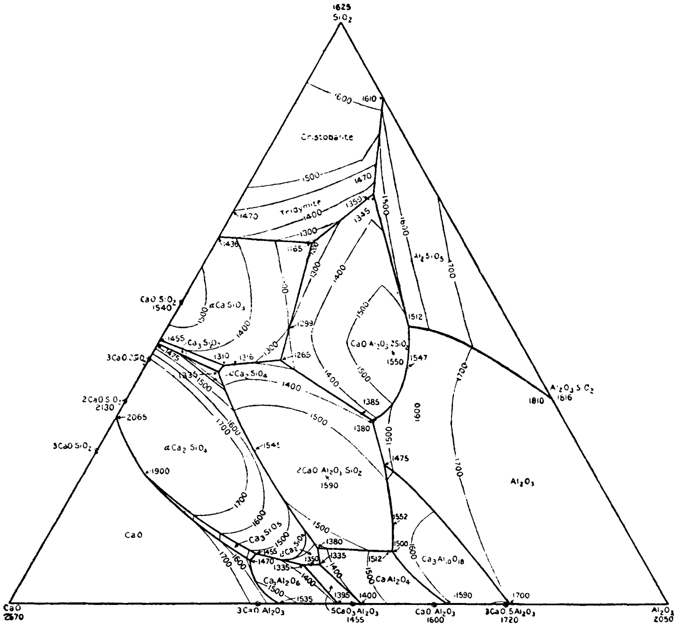

FIG. 11.—Equilibrium diagram of the system $CaO\text{-}Al_2O_3\text{-}SiO_2$. (After Rankin and Wright.)

The system $MgO:Al_2O_3:SiO_2$ given in Figure 12 shows the same general condition. If a mass of sillimanite were immersed in molten $MgSiO_3$ and Mg_2SiO_4 in equal parts, a layer around the inclusion, which might have the bulk composition 75 per cent sillimanite, 25 per cent the above mixture, would consist at higher temperatures of corundum and liquid; at lower temperatures, of sillimanite, spinel, and liquid; and at still lower temperatures, of sillimanite, spinel, and cordierite.

It should be realized that these conditions we have pictured as occurring about sillimanite inclusions are transient states. We may deduce from an equilibrium diagram the condition of a certain layer about an inclusion, but the system as a whole is not in equilibrium

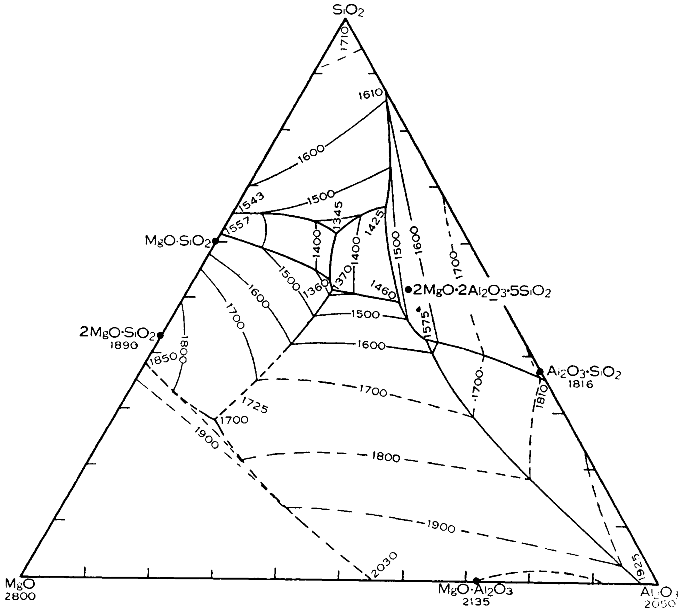

FIG. 12.—Equilibrium diagram of the system $MgO\text{-}Al_2O_3\text{-}SiO_2$. (After Rankin and Merwin.)

since there are composition gradients about these inclusions. Nevertheless this changing state might become fixed and be revealed as a result of complete consolidation of the mass.

The actual magma by which the schist inclusions were attacked may be regarded as showing the combined effects of the anorthite liquid and the magnesian liquid of the experimental systems. It is true the magma did not correspond definitely with any such mixture of anorthite and magnesian silicate, but it was closely related, consisting mainly of plagioclase and magnesian silicates, and its effect on sillimanite-rich inclusions might reasonably be similar.

The effect was indeed very similar, for the sillimanite-rich inclusions are found to be changed by the magma to masses rich in corundum, spinel, and cordierite, with other related minerals. It is inclusions that have been thus affected that constitute the emery deposits. They represent the reaction between the magma and inclusions arrested midway. No doubt many inclusions completely disappeared, becoming an integral part of the igneous rock in virtue of reactions involving adjustment of composition of existing phases. (See p. 549.) The feldspathic emery and the noritic emery may, from this point of view, be regarded as inclusions approaching their final disappearance.

These transient states in which inclusions may be very rich in certain substances are no doubt of some importance in differentiation. Localized masses in process of reaction with the general mass may move, say in response to gravity, and their accumulation may give rise to bodies rich in minerals formed during the reactions. All up and down the Appalachian Mountain system of Eastern North America there are intrusive masses showing ultrabasic differentiates with dunite as the extreme and with associated peridotites and pyroxenites frequently rich in rhombic pyroxene, saxonite, websterite and enstatolite itself. These are usually, perhaps always, intrusive into slates and mica schists that were originally aluminous sediments, the Farnham slates of Quebec, the Savoy and Rowe schists of New England, the Manhattan of New York, the Wissahickon of Pennsylvania and Maryland, and the Carolina gneiss of the Southern States. These have perhaps had an important influence in emphasizing differentiates of the types mentioned above. There are, moreover, corundum deposits, either as emery or in purer forms, in frequent association with these ultra-basic rocks and in some cases the origin and accumulation of corundum may be referred to processes outlined above. Gordon has demonstrated a different origin for some of them,[1] but the action here described seems unquestionable for the Cortlandt emery and the gangue minerals of some of the Carolina deposits strongly suggest a similar origin. These gangue minerals are basic plagioclase, sillimanite and cyanite. That such minerals together with corundum could form from basic magnesian rocks by simple differentiation is very doubtful.[1]

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[1] Formation by reaction between pegmatite and serpentine. S. G. Gordon, *Proc. Acad. Natural Sci. Philadelphia*, Part I (1921), p. 169.

The progressively selective nature of the reaction between magma and inclusions that is shown by these Cortlandt examples and the theoretical considerations discussed in connection therewith demonstrate that a former statement of mine that "the formation of an obviously hybrid rock should, apparently, be the normal result of assimilation"[2] is erroneous and that Daly's objections thereto are justified.[3] Daly's objections are based on considerations other than those raised above and refer rather to the changes that may occur in a *superheated* magma during the slow diffusion into it of xenolithic material. We may recall here that the reactions herein described are those that are to be expected between *saturated* magma and schist inclusions. The fact that the reactions are selective in a way that matches the expectation may presumably be regarded as evidence that the magma was saturated.

Recognition of the probable saturated condition of the magma is of importance because it shows that there could not have been formed, at any time, a liquid whose composition was simply the sum of that of the original magma and the inclusions. Even that portion of the foreign matter which becomes a part of the liquid does so only by precipitating phases with which the magma is saturated and must itself be of a composition toward which the liquid may go spontaneously by fractional crystallization. So in the case of the Cortlandt series various diorites, some syenite and a considerable amount of granite (first recognized by Berkey as a part of the series)[4] were formed by differentiation as they would have been under the same conditions without reaction with slate material, though presumably the amount of "acid" differentiates was augmented by its addition.

Another suggestion concerning the incorporation of slaty rocks in basic magmas may be made at this point. In the neighboring state of Connecticut there occurs a group of rocks showing a striking resemblance to the Cortlandt series.[1] With these are associated nickeliferous sulphide deposits of magmatic origin.[2] This association is highly characteristic, examples of norite and related rocks with nickeliferous sulphides being too familiar to require special enumeration. It seems possible that the incorporation of slaty rocks may be of importance not only in connection with the formation of norite but also of the sulphide deposits, for slaty rocks are very commonly pyritic. At first thought it might seem that the addition of pyrite to a basic magma would not account for the separation from it of the sulphides commonly found in such nickel deposits. However, if pyrite, say as globules of immiscible liquid, remained long immersed in a basic magma it would be subject to the same kind of modification of composition as is any other foreign matter. In short, it would have its composition changed to such sulphides as are particularly insoluble[3] in such magma. Thus if iron, nickel, copper sulphides could separate from such a magma by normal processes, were they present in sufficient amount, then immersed pyrite would be changed to just such iron, nickel, copper sulphides. It seems worthy of consideration, therefore, that the sulphide deposits associated with norites may often be *reconstituted* deposits having their ultimate origin in the incorporation of pyritic slates. Indeed at Sohland and Schweidrich on the Saxony-Bohemia border typical ores of this kind are intimately associated with masses representing what we have termed the transient state of slate inclusions, that is, with masses rich in spinel, sillimanite and corundum.[4]

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[1] See Rankin and Merwin, "The Ternary System MgO-Al_2O_3-SiO_2," *Amer. Jour. Sci.*, Vol. XLV (1918), p. 325.

[2] N. L. Bowen, *Jour. Geol.*, Supplement to Vol. XXIII (1915), p. 85.

[3] R. A. Daly, *Jour. Geol.*, Vol. XXIII (1918), p. 126.

[4] C. P. Berkey, *Science*, Vol. XXVIII (1908), p. 575.

In connection with the formation of norite and perhaps of sulphide deposits, through the influence of absorbed slates, it should be realized that the action is probably an emphasis upon normal processes. It may very well be, however, that if there were no argillaceous sediments norites would be of much rarer occurrence than they are.

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[1] W. H. Hobbs, *Festschrift v. H. Rosenbusch.*, pp. 25–48. Stuttgart, 1906.

[2] Ernest Howe, *Economic Geol.*, Vol. X (1915), p. 330.

[3] Probably as liquid, i.e., immiscible.

[4] Beyschlag, Vogt, Krusch, Truscott, *Ore Deposits,* Vol. I, p. 299, London, 1914.

THE ACTION OF BASIC MAGMAS ON SILICEOUS SEDIMENTS

A number of examples of argillaceous quartzites are known that have been invaded by basaltic magma and in which it is believed by some investigators that absorption of the siliceous sediments by the magma has occurred. Two carefully studied examples are the Pigeon Point sill of Minnesota[1] and the Moyie sills of British Columbia.[2] Such quartzites may again be regarded as consisting of material belonging to a later stage of the reaction series than basaltic magma, together with a certain surplus. The former, corresponding in composition with some acid igneous rock, should be capable of becoming part of the liquid magma by precipitating its heat equivalent of the phases with which the magma is saturated. There is no theoretical objection, therefore, to the belief that a certain amount of the inclusions could be incorporated in this manner even though the magma is saturated. It should be borne in mind, however, that the material that can thus become a part of the liquid must be of a composition toward which the magma could change spontaneously by fractional crystallization. Once incorporated, it requires, to produce the acid differentiates that were there formed, the same conditions of crystallization as would have produced an acid differentiate from the uncontaminated magma. In all of these examples the normal course of differentiation is the primary consideration. The extent to which incorporated material contributed to the bulk of the acid differentiate may not have been important in these small bodies even though there is plain evidence of incorporation.

At both localities mentioned evidence of some incorporation is unquestionable. About inclusions of the sedimentary rocks reaction rims of a granitic nature have been formed. We have seen on page 529 that the reaction should emphasize, in the liquid around the inclusion, material belonging to a later stage of the reaction series (i.e., toward which the magma can crystallize), and this should not be intermediate in composition between magma and inclusion. Corresponding with this deduction we find that the rims about the xenoliths are not simply melted xenolith but essentially normal igneous material of a late stage of the reaction series. The reaction-rim stage is a temporary one except in so far as it may be preserved about some inclusions by exhaustion of the magma. Others disappear entirely by diffusion of the rim material into the magma and distribution (with possible precipitating effects) of any surplus material. Thus the liquid is pushed onward in the reaction series, not only through addition of the rim material, but also because this necessitates some precipitation of the early-formed minerals from the basic magma. Further fractional crystallization may therefore give differentiates identical with, or closely related to, the reaction-rim material, but normal differentiation might have given it also.

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[1] W. S. Bayley, *U.S. Geol. Survey, Bull. 109.* R. A. Daly, *Amer. Jour. Sci.*, Vol. XLIII (1917), p. 423.

[2] R. A. Daly, *Geol. Survey Can., Mem. 38,* p. 226. S. J. Schofield, *Geol. Survey Can., Museum Bull. No. 2.*

Inclusions of some acid sediments, richly charged with volatile substances (mainly water) and immersed in a basic magma under conditions permitting their retention of this volatile matter, might, theoretically, be converted to liquid in toto. Actually, few inclusions show any such effect, from which fact it may be assumed that the conditions mentioned are seldom realized. That the reaction effect discussed is the important one quantitatively seems unquestionable.

EFFECTS OF GRANITIC MAGMA ON INCLUSIONS OF SEDIMENTARY ORIGIN

In discussing the reaction of magmas with inclusions we have, in the case of basaltic magma, made some reference to the superheated condition. Daly points to basaltic magma as the heat bringer, and has presented evidence that such magma enters into igneous-rock economy on a different basis from all other magmas.[1] If this be true, and his reasons seem to me convincing, basaltic magma is the one magma that may, presumably, be assumed to have superheat on some occasions. All other magmas, whether they may be formed by differentiation of basaltic magma or by differentiation of syntectic magma must usually be saturated, unless it be that locally, at volcanic vents, a special source of heat is available. This possibility has little quantitative petrogenic significance and it is perhaps a realization of the commonly saturated condition of other magmas that has led Daly to adopt basaltic magma as his solvent. Thus all of Daly's syntectics are of *basaltic magma* with various types of foreign matter. We have already seen, however, that the saturated condition is no bar to a *reaction* between magma and inclusions. This fact is as true of intermediate magmas as of any others and the same principles apply to them.

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[1] R. A. Daly, *Igneous Rocks and Their Origin*, p. 458.

If the foreign material belongs to an earlier stage of the reaction series the tendency is to make it over into those phases with which the magma is saturated and to precipitate a further amount of these phases from the magma itself. If the foreign material belongs to a later stage of the reaction series it tends to become a part of the liquid by precipitating phases with which the magma is saturated.

Sediments do not belong in the reaction series at all and certain types of sediments contain material belonging in both the above classes and both effects may be obtained. Our chief purpose here is to consider principles, and it seems unnecessary, therefore, to discuss individually the action of various intermediate magmas on various foreign inclusions.

It is perhaps desirable, however, to discuss the action of granitic magma on sediments, its action on igneous inclusions having already been described. For the reason mentioned above, only saturated granitic magma will be considered. Quartzites and slaty rocks offer no special problem. They are readily transformed into phases with which the granite is saturated, an action that any magma will accomplish in so far as the composition of the sediment permits. The conversion of inclusions of such rocks by granitic magma into masses of quartz, feldspars, and micas, in varying proportions, should therefore be the result. A certain amount of mechanical disintegration might cause the strewing about of these products in such a way as to make them an integral part of the mass but there should be no solution. Intermediate steps might see the formation of such minerals as sillimanite, garnet, and others characteristic of contact rocks, but these should be temporary or should survive only because of exhaustion of the liquid.

The kind of effect that sillimanite produces by reaction with basic magmas, namely, the precipitation of orthopyroxene and basic plagioclase is not to be expected in granitic magma. Rather should we expect precipitation of the micas in acid magmas, and formation of orthopyroxene in such magmas is to be referred to other causes than that proposed by Evans[1] and here adopted for basic rocks.

When we turn to the case of carbonate rocks we find that the reaction with granitic magma is of a different nature. It is often observed that wall rock and inclusions of carbonates are altered to silicate minerals.[2] It has been assumed by some investigators, therefore, that silica has been subtracted from the granitic liquid and that this may occur to such an extent that some of the feldspar molecules are transformed into the less siliceous, feldspathoid molecules with consequent formation of alkaline rocks. This assumed action is said by certain writers to be in agreement with Daly's theory of the origin of alkaline rocks. We have seen above, however, that Daly assumes that superheated basaltic magma is the starting point for all his syntectic magmas and that alkaline rocks are differentiates of some of these syntectics, principally those formed with carbonate rocks. We have pointed out on a preceding page that, if adequately superheated basalt were available, it might form, by solution of carbonates, a melilite basalt and, given the latter, alkaline differentiates seem not impossible and so indeed some alkaline rocks may be formed. Not all alkaline rocks can be so explained, for much nephelite syenite shows intimate genetic relations with granites and on Daly's general theory the original basaltic magma would require to be silicated by solution of acid material to form the granite and desilicated by solution of carbonates to form the nephelite syenite. That the differentiates should show evidence of both seems out of the question. The solution of foreign matter must result in either desilication or silication according to the preponderance of one or the other type of foreign matter and subsequent differentiates should be in conformance with one or the other but not both.

This brings us back to the question whether a nephelite syenite, intimately associated with a granite, could have been formed as a result of desilication of the granite by carbonate inclusions, that is, back to the question of the effect of granitic magma on carbonate inclusions.

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[1] J. W. Evans, *Quar. Jour. Geol. Soc.*, Vol. XLVIII (1921), p. 133.

[2] For example in the large-scale production of amphibolites in the Haliburton-Bancroft area. Adams and Barlow, *Can. Geol. Surv., Mem. No. 6* (1910).

We have noted the silication of the inclusions and the consequent supposed desilication of the liquid. In discussing investigated systems we have already found, however, that saturated liquids cannot have ingredients subtracted from them at random without causing precipitation of other ingredients so that the effect on the liquid is not mere impoverishment in the ingredient subtracted. This may perhaps be made clear by a simple example. If we had a solution of salt at −20° C, and any hypothetical substance was placed in the solution that withdrew the salt from it, the result would not be simply the leaving behind of liquid water. The reason is simply that liquid water cannot exist at −20° C and the actual result would be that, as each small amount of salt was removed, a small amount of ice would form and, when all the salt was withdrawn, all of the water would have become ice. For the maintenance of liquidity, the salt and the water are necessary each to the other. And so it must be with a saturated granitic solution. Remove the silica from it and other substances must be precipitated. Now the reaction of granitic magma with inclusions of carbonate rock is not a simple addition of silica to the latter but usually other substances are added as well, these being such as to convert the inclusions ultimately into diopsidic pyroxene or hornblende. The reason for the formation of these phases is that they belong at an earlier stage of the reaction series than the biotite with which granitic magma is normally saturated. The subtraction of the substances necessary to produce these minerals must, for reasons outlined above, cause concomitant precipitation of the other phases normally formed from granitic magma, principally feldspar. Thus the action described must bring about an exhaustion of the liquid by causing precipitation. There seems to be no reason for believing that it could first exhaust the free silica, leaving a feldspar-rich *liquid*, then, upon further action, cause removal of some of the silica from the feldspar *liquid* leaving a *liquid* containing feldspathoid molecules.

A reaction of the kind described, that is, a using up of some silica to form diopside with the consequent precipitation of feldspar and quartz, would seem to me to be the mode of formation of the diopside-bearing variety of the Beckett gneiss, of which Eskola has written a description and interpretation.[1] I visited the localities with Dr. Eskola, and in my opinion the transformation of the solid dolomite into solid diopside with its effect upon the granitic liquid was the dominant action in the production of the types of gneisses there found, and of their banding, rather than actual solution of the dolomite or skarn in the granite and subsequent differentiation of the syntectic liquid. It must be admitted, however, that the solubility of $CaCO_3$ in magmas is probably greater than that of CaO and that under conditions permitting the retention of CO_2 an amount of limestone might be dissolved greater than that suggested by the reaction effects already discussed. The usual free conversion of limestone into silicates indicates, however, that it is not commonly so dissolved.

The formation of basic silicates, without the production of feldspathoids, seems to be the ordinary result of the action of granitic magma on limestone inclusions. Thus, in the granitic portions of the Bushveldt laccolith altered limestone inclusions are surrounded by a halo of dioritic material, but not by alkaline rock.[2] Other examples might be given; in fact, the ordinary effects of granite on limestone seem to be those we have deduced for a saturated granitic magma.

In one locality the alkaline facies of the Bushveldt complex is, it is true, intimately associated with a mass of limestone, and as a result of a study of this locality Shand has concluded that there is some connection between the production of the feldspathoids and the desilicating action of the magma. Apparently Shand does not believe that the entire production of nephelite is due to this action but rather that a nephelite syenite magma becomes ijolite by desilication.[3] This is a quite different matter from the production of the original nephelite syenite magma by such desilication. No theoretical objection can be raised against the belief that interaction with limestone could reduce the amount of feldspar and increase the amount of feldspathoid in a magma already capable of precipitating both of these. Such adjustment of the relative amounts of minerals we have found to be a common effect of inclusions.

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[1] P. Eskola, *Jour. Geol.*, Vol. XXX (1922), pp. 265–94.

[2] Oral communication. Professor Brouwer.

[3] S. J. Shand, *Trans. Geol. Soc. South Africa*, Vol. XXII (1921), pp. 144–46.

It is probable that alkaline rocks are ordinarily produced by crystallization differentiation from subalkaline magmas. A possible method in the case of a leucite-bearing rock has been demonstrated by Morey and Bowen, who show that a liquid of the composition of orthoclase or even one with a moderate excess of silica over the amount necessary to form orthoclase will precipitate leucite as the first-formed crystals.[1] If an orthoclase-rich liquid came into being by fractional crystallization of a more basic magma it might, under the appropriate conditions, show the above effect. The fact that the excess silica must be no more than a small amount should be noted, for this fact renders it possible that limestone may, in spite of the many objections that have been raised above, have some influence in promoting the formation of alkaline rocks. The influence is, however, an emphasizing of a normal tendency rather than a fundamental necessity. This we have found to be a general rule in connection with the effects of inclusions. If the differentiation of the magma which gave rise to the orthoclase-rich liquid took place in the presence of a supply of limestone inclusions this would tend to reduce to a minimum any excess silica that might otherwise be associated with the orthoclase. Thus the normal tendency of the orthoclase to break down into leucite under the proper conditions would be free to assert itself. We may therefore accept the possibility that reaction with limestone may emphasize the tendency toward the formation of an alkaline differentiate, though it is not essential to it. Other factors, such as the failure of olivine to form at an early stage in the magma's history, or the free resorption of such olivine as does form, may also assure a low excess of silica at a late stage with likelihood of the separation of feldspathoids. The tendency of feldspathoid to separate under these conditions has been demonstrated as yet only for leucite, but the frequent intimate association of leucitic and nephelitic rocks renders it probable that the factors governing the formation of the nephelitic rocks are not unrelated.

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[1] *Amer. Jour. Sci.*, Vol. IV (1922), pp. 1–21.

DEDUCTIONS TO BE COMPARED WITH OBSERVED RESULTS

Throughout the foregoing study of the reactions between inclusions and magma, attention has been directed mainly to its theoretical aspects, that is, to deducing from equilibrium considerations what reactions should occur, together with the effects of these upon the further crystallization of the magma. All of these deductions can be put to the test by observation of what has actually occurred, in particular by a study of the reaction rims formed about inclusions. It should not be expected that each inclusion will tell the whole story, but a general study of inclusions should do so. Not all the differentiates that might later form from the hybrid mass need be shown by the reaction rims, but certainly there should be formed some whose relationship to these possible later differentiates is established by their frequent association in many areas.

In some instances examples have been cited which appear to show that the expected reactions do occur. Such are the formation of granitic reaction rims by the action of basaltic magma on acidic rocks, the making of basic inclusions into biotite-rich masses by granitic magma, and others. The formation of alkaline rocks by the action of ordinary magmas on limestones is, at present, incapable of support on the above grounds. No example is known where inclusions of limestone, contained in an ordinary rock, are surrounded by reaction rims of feldspathoid-bearing rock. It is true that limestones and alkaline rocks are often intimately associated, but there is no assurance that the magma was not already an alkaline magma before it acquired this association. As we have already pointed out, this appears to be the conclusion that Shand reaches concerning the Sekukuniland occurrence, though he favors also the conception that the limestone emphasized its alkaline nature.

In the Fen area of Norway, one of the newer areas to which the limestone-syntectic hypothesis has been applied, there is a very striking association of alkaline rocks and carbonate rocks.[1] However, nothing there displayed demonstrates a change of subalkaline magma to alkaline magma through the influence of the carbonate rock. No support in the way of reaction rims of the appropriate kind has yet been found for the limestone-syntectic hypothesis. Some such support is desirable before the hypothesis can be accepted, even though there is reason to believe, as pointed out above, that the presence of limestone might emphasize the normal tendency of magmas to give an alkaline differentiate.

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[1] Cf. W. C. Brögger, "Die Eruptivgesteine des Kristianiagebietes IV," *Vid. Selsk. Skr. I. Mat. Naturv. Klasse* (1920).

SUMMARY

The question whether magmas can dissolve large quantities of foreign inclusions is one that has been much debated by petrologists. Some have claimed great powers for magmas in this respect and in addition have assigned a dominant rôle in the production of differentiation to such solution of foreign matter. Others have insisted that magmas have not the necessary heat content to enable them to give significant effects of this kind. A study of some simple equilibrium diagrams, with the object of determining the heat effects connected with solution, gives every reason for believing that the effect is a large absorption of heat, usually of the order of magnitude of the latent heat of melting. For simple solution, then, it is unquestionable that large amounts of heat will be required.

Those who believe in the actuality of the solution of considerable amounts of foreign matter in magmas have usually realized this fact and have sought a source of the heat in magmatic superheat of great amount, that is, in a large excess of temperature of the magma above its crystallization range. A study of the probabilities of the case and of the usual effects of magmas upon inclusions leaves little reason for believing that magmas can ordinarily have any considerable superheat.

Unquestionably, then, the observed effects of magmas upon inclusions are usually to be referred to an action other than the direct solution of inclusions in superheated magma. An application of the conception of the reaction series to the solution of the problem affords an explanation of the effects of magmas, even though saturated. Certain principles governing the effects of liquid upon inclusions belonging to reaction series can be developed by studying the equilibrium diagrams of systems involving both continuous and discontinuous reaction series. In this manner it can be decided definitely that a liquid saturated with a certain member of a reaction series is effectively supersaturated with all preceding members of that series. It cannot dissolve such members but can only react with them to convert them into the members with which it is saturated. The reaction is not a simple subtraction from the liquid of the material necessary for this transformation, but some precipitation from the liquid itself is involved and the liquid ordinarily maintains its position on the same saturation surface. The products of crystallization from the liquid and the possible course of fractional crystallization are thus unaffected.

On the other hand, a liquid saturated with a certain member of a reaction series is unsaturated with all subsequent members of the series. Inclusions consisting of these later members can become a part of the liquid by a sort of reactive solution, the heat of solution of inclusions being supplied by the precipitation of their heat equivalent of the member of the series with which the liquid is saturated. It should be noted that the material that can by this reactive process become a part of the liquid must consist of a later member of the reaction series, that is, must be material toward which the liquid could pass spontaneously by fractional crystallization. The net effect upon the liquid is, then, to push it onward upon its normal course.

In Table II the products of crystallization of subalkaline magmas are arranged as reaction series, as definitely as may be in such complex series. The action of magmas upon foreign inclusions of igneous origin may be deduced from this arrangement of the crystalline products as series by application of the principles developed from the above study of simple systems. Thus we find that a granitic magma saturated with biotite cannot dissolve olivine, pyroxene, or amphibole, but can only react with them to convert them into biotite, the phase with which it is saturated. Or, stated more generally, no saturated magma can dissolve inclusions consisting of minerals belonging to an earlier stage of the reaction series (usually more basic).

Saturated basic magma, on the other hand, will react with inclusions belonging to a later stage of the reaction series (more acidic), the reaction being of such a nature that the inclusions become a part of the liquid by precipitating their heat equivalent of the phases with which the magma is saturated (basic minerals). The inclusions, it should be noted, must be of a composition toward which the liquid could pass spontaneously by fractional crystallization. Thus saturated basaltic magma can dissolve granitic inclusions by precipitating basic minerals and the granitic material passing into solution then becomes a contribution to the normal granitic differentiate that may form by fractional crystallization if the conditions are appropriate.

The behavior of inclusions of sedimentary origin is more complicated since sedimentary material does not belong in the reaction series. A consideration of the extent and nature of the variation of composition possible in the crystalline phases formed from a magma shows that the incorporation of considerable amounts of sedimentary material would ordinarily bring about merely an adjustment in the composition and relative proportions of existing phases. As a result of the non-appearance of new phases, the general course of fractional crystallization is unaffected. In general, the adjustment noted takes place through precipitation of the phases with which the magma is saturated. As an example it may be stated that the addition of highly aluminous sediments to basic magma should bring about the formation of anorthite and enstatite molecules at the expense of diopside molecules and should therefore cause the precipitation of crystals rich in anorthite and enstatite. Such action may have been important in the formation of many norites. The foreign material becomes a part of the general mass as a result of reaction and precipitation rather than by simple solution.

The Cortlandt series of New York, with its inclusions, affords an illustration of the behavior of aluminous sediments in basic magma. Such sediments may be regarded as consisting in part of material corresponding in composition with igneous material late in the reaction series, together with a certain excess, which is highly aluminous. The former may become a part of the liquid by the method of reactive solution already described. There results the piling-up of the highly aluminous excess in the inclusions, with formation of such minerals as sillimanite. Moreover, as a consequence of what may be somewhat loosely called the instability of sillimanite in contact with liquid rich in anorthite or magnesian silicates, alumina is set free as corundum. This condition is transient, however, and even these residues from the inclusions may become a part of the general mass as a result of the reactive precipitation noted above. The net result is the formation of noritic material with an increase in amount of the acidic differentiate normally possible.

The addition of limestone to basaltic magma may perhaps give rise to a liquid capable of precipitating melilite in some cases and from such a liquid it is possible that some alkaline rocks may form by further differentiation. It does not seem possible that limestone inclusions can desilicate a granitic magma in such a way as to give rise to a liquid capable of precipitating feldspathoids. However, if limestone inclusions were present during the differentiation of the more basic liquid from which the granitic liquid may have formed, the presence of such inclusions might reduce the amount of free silica associated with the alkaline feldspar in this liquid to such an extent that the normal tendency of orthoclase to break down into leucite would manifest itself. Thus rocks bearing leucite, and possibly other feldspathoids, might form, but influences prevailing during early stages of differentiation, other than the presence of foreign matter such as limestone, may likewise lead to the formation of leucite at a late stage.

In conclusion, it may be stated, therefore, that magmas may incorporate considerable quantities of foreign inclusions, both by the method of reactive solution and by reactive precipitation, and such action may have been important in connection with the production of certain individual masses. Thus some norites may have been produced as a result of the reactions discussed above, some granites may have had their mass augmented by reactive solution of granitic inclusions in the magma from which they differentiated, some alkaline rocks may have been formed as a result of the presence of limestone inclusions in the liquid from which they differentiated. All of these actions are, however, an emphasizing of normal processes possible in the absence of foreign matter. It is doubtful whether the presence of foreign matter is ever essential to the production of any particular type of differentiate.

WASHINGTON, D.C.
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